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_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_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/GINKG↩O_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_LIBRA↩RY_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_RE↩LPATH>;%PATH%"
  - powershell:

    ```
    env
        ATH="<PROJECT_BINARY_DIR/GINKGO_WINDOWS_SHARED_LIBRARY_RELPA↩
        TH>;
    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 environement 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 environement variable CXX_FLAGS or CMAKE_CXX_FLAGS

- Build Ginkgo in *MinGW*: If encountering the issue cc1plus.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 NVIDIA 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 Correctly installing HIP toolkits and dependencies for Ginkgo

In general, Ginkgo's HIP backend requires the following packages:

- HIP,
- hipBLAS,
- hipSPARSE,
- Thrust.

It is necessary to provide some details about the different ways to procure and install these packages, in particular for NVIDIA systems since getting a correct, non bloated setup is not straightforward.

For AMD systems, the simplest way is to follow the instructions provided here which provide package installers for most Linux distributions. Ginkgo also needs the installation of the hipBLAS and hipSPARSE interfaces. Optionally if you do not already have a thrust installation, [the ROCm provided rocThrust package can be used](https://github.com/ROCmSoftwarePlatform/rocThrust).

For NVIDIA systems, the traditional installation (package hip_nvcc), albeit working properly is currently odd↩ : it depends on all the hcc related packages, although the nvcc backend seems to entirely rely on the CUDA suite. [See this issue for more details](https://github.com/ROCmSoftwarePlatform/hipBLA↩ S/issues/53). It is advised in this case to compile everything manually, including using forks of hipBLAS and hipSPARSE specifically made to not depend on the hcc specific packages. Thrust is often provided by CU↩ DA and this Thrust version should work with HIP. Here is a sample procedure for installing HIP, hipBLAS and hipSPARSE.

```
# HIP
git clone https://github.com/ROCm-Developer-Tools/HIP.git
pushd HIP && mkdir build && pushd build
cmake .. && make install
popd && popd
# hipBLAS
git clone https://github.com/tcojean/hipBLAS.git
pushd hipBLAS && mkdir build && pushd build
cmake .. && make install
popd && popd
# hipSPARSE
git clone https://github.com/tcojean/hipSPARSE.git
pushd hipSPARSE && mkdir build && pushd build
cmake -DBUILD_CUDA=ON .. && make install
popd && popd
```

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 backend. 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
```

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.

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.

By default, 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. Note that, if the external packages were not installed to the default location, the CMake option -DCMAKE_PREFIX_PATH=<path-list> needs to be set to the semicolon (;) separated list of install paths of these external packages. For more Information, see the CMake documentation for CMAKE_PREFIX_PATH for details.

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

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

When applicable (e.g. for GTest libraries), a ; separated list can be given to the TPL_<package>_{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 us uncompressing the archive). Additionally, the benchmark runs usually take a long time (SpMV benchmarks on the complete collection take roughly 24h using the K20 GPU), and will stress the system.

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}` - 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.
- `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
./agregate < list.json > agregate.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/mas
   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/utils/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}` - 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 is0. *DRY_RUN={true, false}- If set totrue`, 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,adaptive-jacobi,ilu,parict,parilu,parilut,none} 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} - the solvers which should be benchmarked. Multiple options can be passed. The default is cg.
- 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.
- 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.

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.

5.1 Table of Contents

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Other programming comments

- C++ standard stream objects
- Warnings
- Avoiding circular dependencies

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) 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 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 betweeen 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 and HIP 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 and HIP, 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 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}
}
```

6.0.2 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}
}
```

6.0.3 On SpMV 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&amp;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)}
}
```

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**.

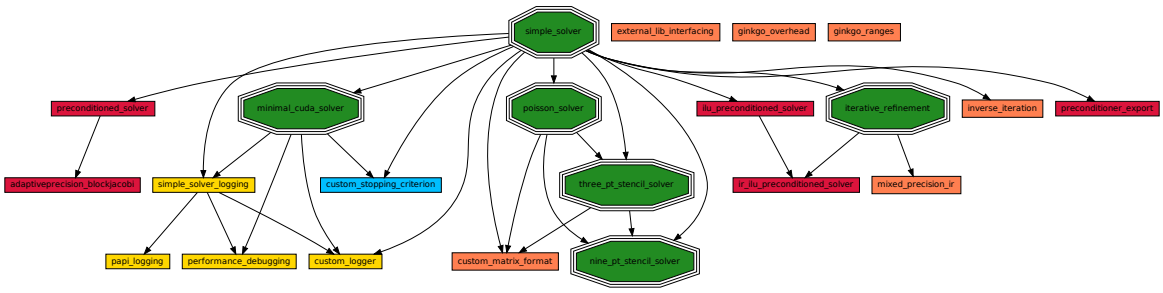
By default, all Ginkgo examples are built using CMake.

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`

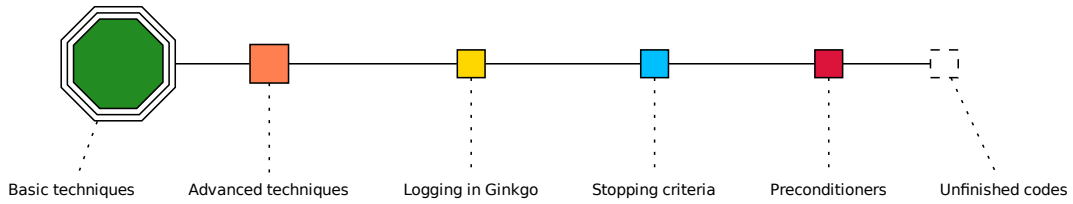
By default, Ginkgo is compiled with at least `-DGINKGO_BUILD_REFERENCE=ON`. To execute on a GPU, you need to have a GPU on the system and must have compiled Ginkgo with the `-DGINKGO_BUILD_CUDA=ON` option.

Connections between example programs

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



Legend:



Example programs

The simple-solver program	A minimal CG solver in Ginkgo, which reads a matrix from a file.
The minimal-cuda-solver program	A minimal solver on the CUDA executor than can be run on 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.
twentyseven_pt_stencil_solver	Using a twentyseven point 3D stencil to solve the poisson equation with array views.
The external-lib-interfacing program	Using Ginkgo's solver with the external library deal.II.
The custom-logger program	Creating a custom logger specifically for comparing the recurrent and the real residual norms.
The custom-matrix-format program	Creating a matrix-free stencil solver by using Ginkgo's advanced methods to build your own custom matrix format.
The inverse-iteration program	Using Ginkgo to compute eigenvalues of a matrix with the inverse iteration method.
The simple-solver-logging program	Using the logging functionality in Ginkgo to get solver and other information to diagnose and debug your code.
The papi-logging program	Using the PAPI logging library in Ginkgo to get advanced information about your code and its behaviour.
The ginkgo-overhead program	Measuring the overhead of the Ginkgo library.

The custom-stopping-criterion program	Creating a custom stopping criterion for the iterative solution process.
The ginkgo-ranges program	Using the ranges concept to factorize a matrix with the LU factorization.

Example programs grouped by topics

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, twentyseven_pt↩ _stencil_solver, 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

Advanced techniques

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 <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;
```

Figure out where to run the code

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

```
            gko::HipExecutor::get_num_devices() > 0) {
    exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
} else {
    std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
    std::exit(-1);
}
```

Read data

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

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::ResidualNormReduction<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]: 2.04779
```

Comments about programming and debugging

The plain program

```
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*******************************<GINKGO LICENSE>******************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
```

```
    }
    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::ResidualNormReduction<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 custom-logger program

The simple solver with a custom logger example..

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

Introduction

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

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

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

About the example

Each example has the following sections:

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

The commented program

Include files

This is the main ginkgo header file.
```
#include <ginkgo/ginkgo.hpp>
```

Add the fstream header to read from data from files.
```
#include <fstream>
```

Add the C++ iomanip header to prettify the output.
```
#include <iomanip>
```

Add formatting flag modification capabilities.
```
#include <ios>
```

Add the C++ iostream header to output information to the console.
```
#include <iostream>
```

Add the string manipulation header to handle strings.
```
#include <string>
```

Add the vector header for storing the logger's data
```
#include <vector>
```

Utility function which 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 residual norm:" « std::endl;
std::cout « '|' « std::setw(10) « "Iteration" « '|' « std::setw(25)
```

```
          « "Recurrent Residual Norm" « '|' « std::setw(25)
          « "True Residual Norm" « '|' « std::endl;
```

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

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

Print the data one by one in the form

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

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

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

Print a separation line

```
    std::cout « '|' « std::setfill('-') « std::setw(11) « '|'
              « std::setw(26) « '|' « std::setw(26) « '|'
              « std::setfill(' ') « std::endl;
}
using gko_dense = gko::matrix::Dense<ValueType>;
using gko_real_dense = gko::matrix::Dense<RealValueType>;
```

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

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

If the solver shares a residual norm, log its value

```
if (residual_norm) {
    auto dense_norm = gko::as<gko_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);
}
```

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 iteration numbers

```
    mutable std::vector<std::size_t> iterations{};
};
int main(int argc, char *argv[])
{
```

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

```
using 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.

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

Reading your data and transfer to the proper device.

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

Note

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

```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
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::ResidualNormReduction<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 residual norm:
| Iteration|  Recurrent Residual Norm|       True Residual Norm|
|----------|-------------------------|-------------------------|
|         0|             4.358899e+00|             4.358899e+00|
|         1|             2.304548e+00|             2.304548e+00|
|         2|             1.467706e+00|             1.467706e+00|
|         3|             9.848751e-01|             9.848751e-01|
|         4|             7.418330e-01|             7.418330e-01|
|         5|             5.136231e-01|             5.136231e-01|
|         6|             3.841650e-01|             3.841650e-01|
|         7|             3.164394e-01|             3.164394e-01|
|         8|             2.277088e-01|             2.277088e-01|
|         9|             1.703121e-01|             1.703121e-01|
|        10|             9.737220e-02|             9.737220e-02|
|        11|             6.168306e-02|             6.168306e-02|
|        12|             4.541231e-02|             4.541231e-02|
|        13|             3.195304e-02|             3.195304e-02|
|        14|             1.616058e-02|             1.616058e-02|
|        15|             6.570152e-03|             6.570152e-03|
|        16|             2.643669e-03|             2.643669e-03|
|        17|             8.588089e-04|             8.588089e-04|
|        18|             2.864613e-04|             2.864613e-04|
|        19|             1.641952e-15|             2.107881e-15|
|----------|-------------------------|-------------------------|
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
2.10788e-15
```

Comments about programming and debugging

The plain program

```
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(INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE
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*****************************<GINKGO LICENSE>******************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#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 residual norm:" << std::endl;
        std::cout << '|' << std::setw(10) << "Iteration" << '|' << std::setw(25)
                  << "Recurrent Residual Norm" << '|' << std::setw(25)
                  << "True Residual Norm" << '|' << std::endl;
        std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
                  << std::setw(26) << '|' << std::setw(26) << '|'
                  << std::setfill(' ') << std::endl;
        std::cout << std::scientific;
        for (std::size_t i = 0; i < iterations.size(); i++) {
            std::cout << '|' << std::setw(10) << iterations[i] << '|'
                      << std::setw(25) << recurrent_norms[i] << '|'
                      << std::setw(25) << real_norms[i] << '|' << std::endl;
        }
        std::cout.unsetf(std::ios_base::floatfield);
        std::cout << '|' << std::setfill('-') << std::setw(11) << '|'
                  << std::setw(26) << '|' << std::setw(26) << '|'
                  << std::setfill(' ') << std::endl;
    }
    using gko_dense = gko::matrix::Dense<ValueType>;
    using gko_real_dense = gko::matrix::Dense<RealValueType>;
    void on_iteration_complete(const gko::LinOp *,
```

```
                              const gko::size_type &iteration,
                              const gko::LinOp *residual,
                              const gko::LinOp *solution,
                              const gko::LinOp *residual_norm) const override
    {
        if (residual_norm) {
            auto dense_norm = gko::as<gko_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);
        }
        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<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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create());
    } else {
        std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
        std::exit(-1);
    }
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
    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::ResidualNormReduction<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 10

The custom-matrix-format program

The custom matrix format example..

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

Introduction

This example solves a 1D Poisson equation:

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

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

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

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

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

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

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

About the example

The commented program

```
#include <iostream>
#include <map>
#include <string>
#include <omp.h>
#include <ginkgo/ginkgo.hpp>
```

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

```
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 += coefs[2] * b_values[i + 1];
                    }
                    x_values[i] = result;
                }
            }
```

CUDA implementation

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

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

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

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

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

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

```
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 coefs[] = {-1, 2, -1};
    row_ptrs[0] = pos;
    for (int i = 0; i < discretization_points; ++i) {
        for (auto ofs : {-1, 0, 1}) {
            if (0 <= i + ofs && i + ofs < discretization_points) {
                values[pos] = coefs[ofs + 1];
                col_idxs[pos] = i + ofs;
                ++pos;
            }
        }
        row_ptrs[i + 1] = pos;
    }
}
```

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

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

Get number of discretization points

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

Figure out where to run the code

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

Results

Comments about programming and debugging

The plain program

```
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#include <iostream>
#include <map>
#include <string>
#include <omp.h>
#include <ginkgo/ginkgo.hpp>
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_idxs = matrix->get_col_idxs();
    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_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 / (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::cerr « "Usage: " « argv[0] « " DISCRETIZATION_POINTS [executor]"
                 « std::endl;
        std::exit(-1);
    }
    const unsigned int discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100u;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    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);
             }},
            {"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::ResidualNormReduction<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));
```

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

Chapter 11

The custom-stopping-criterion program

The custom stopping criterion creation example..

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

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <string>
#include <thread>
/ **
 * The ByInteraction class is a criterion which asks for user input to stop
 * the iteration process. Using this criterion is slightly more complex than the
 * other ones, because it is asynchronous therefore requires the use of threads.
 * /
class ByInteraction
    : public gko::EnablePolymorphicObject<ByInteraction, gko::stop::Criterion> {
    friend class gko::EnablePolymorphicObject<ByInteraction,
                                              gko::stop::Criterion>;
    using Criterion = gko::stop::Criterion;
public:
    GKO_CREATE_FACTORY_PARAMETERS(parameters, Factory)
    {
        / **
         * Boolean set by the user to stop the iteration process
         * /
        std::add_pointer<volatile bool>::type GKO_FACTORY_PARAMETER_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

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

Declare a user controled boolean for the iteration process

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

Create a new a thread to launch the solver

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

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

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

Results

This is the expected output:

```
.
.
.
.
.
.
[LOG] »> iteration 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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#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#include <string>
#include <thread>
class ByInteraction
    : public gko::EnablePolymorphicObject<ByInteraction, gko::stop::Criterion> {
    friend class gko::EnablePolymorphicObject<ByInteraction,
                                              gko::stop::Criterion>;
    using Criterion = gko::stop::Criterion;
public:
    GKO_CREATE_FACTORY_PARAMETERS(parameters, Factory)
    {
        std::add_pointer<volatile bool>::type GKO_FACTORY_PARAMETER_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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    volatile bool stop_iteration_process{};
    std::thread t(run_solver, &stop_iteration_process, exec);
    std::cout << "Type 'stop' to stop the iteration process" << std::endl;
    std::string command;
    while (std::cin >> command) {
        if (command == "stop") {
            break;
        } else {
            std::cout << "Unknown command" << std::endl;
        }
    }
    std::cout << "User input command 'stop' - The solver will stop!"
              << std::endl;
    stop_iteration_process = true;
    t.join();
}
```

Chapter 12

The external-lib-interfacing program

The external library(deal.II) interfacing example..

Introduction

About the example

The commented program

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

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

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

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

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

Ginkgo's header file

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

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

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

The last step is as in previous programs:

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

AdvectionProblem class declaration

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

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

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

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

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

```
struct AssemblyScratchData {
    AssemblyScratchData(const FiniteElement<dim> &fe);
    AssemblyScratchData(const AssemblyScratchData &scratch_data);
    FEValues<dim> fe_values;
    FEFaceValues<dim> fe_face_values;
};
struct AssemblyCopyData {
    FullMatrix<double> cell_matrix;
    Vector<double> cell_rhs;
    std::vector<types::global_dof_index> local_dof_indices;
};
void assemble_system();
void local_assemble_system(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    AssemblyScratchData &scratch, AssemblyCopyData &copy_data);
void copy_local_to_global(const AssemblyCopyData &copy_data);
```

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

```
    void solve();
    void refine_grid();
    void output_results(const unsigned int cycle) const;
    Triangulation<dim> triangulation;
    DoFHandler<dim> dof_handler;
    FE_Q<dim> fe;
    ConstraintMatrix hanging_node_constraints;
    SparsityPattern sparsity_pattern;
    SparseMatrix<double> system_matrix;
    Vector<double> solution;
    Vector<double> system_rhs;
};
```

Equation data declaration

Next we declare a class that describes the advection field. This, of course, is a vector field with as many components as there are space dimensions. One could now use a class derived from the `Function` base class, as we have done for boundary values and coefficients in previous examples, but there is another possibility in the library, namely

a base class that describes tensor valued functions. In contrast to the usual `Function` objects, we provide the compiler with knowledge on the size of the objects of the return type. This enables the compiler to generate efficient code, which is not so simple for usual vector-valued functions where memory has to be allocated on the heap (thus, the `Function::vector_value` function has to be given the address of an object into which the result is to be written, in order to avoid copying and memory allocation and deallocation on the heap). In addition to the known size, it is possible not only to return vectors, but also tensors of higher rank; however, this is not very often requested by applications, to be honest...

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

```
template <int dim>
class AdvectionField : public TensorFunction<1, dim> {
public:
    AdvectionField() : TensorFunction<1, dim>() {}
    virtual Tensor<1, dim> value(const Point<dim> &p) const;
    virtual void value_list(const std::vector<Point<dim» &points,
                            std::vector<Tensor<1, dim» &values) const;
```

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

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

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

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

```
};
```

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

```
template <int dim>
Tensor<1, dim> AdvectionField<dim>::value(const Point<dim> &p) const
{
    Point<dim> value;
    value[0] = 2;
    for (unsigned int i = 1; i < dim; ++i)
        value[i] = 1 + 0.8 * std::sin(8 * numbers::PI * p[0]);
    return value;
}
template <int dim>
void AdvectionField<dim>::value_list(const std::vector<Point<dim» &points,
                                     std::vector<Tensor<1, dim» &values) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = AdvectionField<dim>::value(points[i]);
}
```

Besides the advection field, we need two functions describing the source terms (`right hand side`) and the boundary values. First for the right hand side, which follows the same pattern as in previous examples. As described in the introduction, the source is a constant function in the vicinity of a source point, which we denote by the constant static variable `center_point`. We set the values of this center using the same template tricks as we have shown

in the step-7 example program. The rest is simple and has been shown previously, including the way to avoid virtual function calls in the `value_list` function.

```
template <int dim>
class RightHandSide : public Function<dim> {
public:
    RightHandSide() : Function<dim>() {}
    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;
    virtual void value_list(const std::vector<Point<dim» &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
private:
    static const Point<dim> center_point;
};
template <>
const Point<1> RightHandSide<1>::center_point = Point<1>(-0.75);
template <>
const Point<2> RightHandSide<2>::center_point = Point<2>(-0.75, -0.75);
template <>
const Point<3> RightHandSide<3>::center_point = Point<3>(-0.75, -0.75, -0.75);
```

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

```
template <int dim>
double RightHandSide<dim>::value(const Point<dim> &p,
                                 const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double diameter = 0.1;
    return ((p - center_point).norm_square() < diameter * diameter
              ? .1 / std::pow(diameter, dim)
              : 0);
}
template <int dim>
void RightHandSide<dim>::value_list(const std::vector<Point<dim» &points,
                                    std::vector<double> &values,
                                    const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = RightHandSide<dim>::value(points[i], component);
}
```

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

```
template <int dim>
class BoundaryValues : public Function<dim> {
public:
    BoundaryValues() : Function<dim>() {}
    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;
    virtual void value_list(const std::vector<Point<dim» &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
};
template <int dim>
double BoundaryValues<dim>::value(const Point<dim> &p,
                                  const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double sine_term =
        std::sin(16 * numbers::PI * std::sqrt(p.norm_square()));
    const double weight = std::exp(-5 * p.norm_square()) / std::exp(-5.);
    return sine_term * weight;
}
template <int dim>
void BoundaryValues<dim>::value_list(const std::vector<Point<dim» &points,
                                     std::vector<double> &values,
                                     const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = BoundaryValues<dim>::value(points[i], component);
}
```

GradientEstimation class declaration

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

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

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

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

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

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

```
class GradientEstimation {
public:
    template <int dim>
    static void estimate(const DoFHandler<dim> &dof,
                         const Vector<double> &solution,
                         Vector<float> &error_per_cell);
    DeclException2(ExcInvalidVectorLength, int, int,
                   « "Vector has length " « arg1 « ", but should have "
                   « arg2);
    DeclException0(ExcInsufficientDirections);
private:
    template <int dim>
    struct EstimateScratchData {
        EstimateScratchData(const FiniteElement<dim> &fe,
                            const Vector<double> &solution,
                            Vector<float> &error_per_cell);
        EstimateScratchData(const EstimateScratchData &data);
        FEValues<dim> fe_midpoint_value;
        const Vector<double> &solution;
        Vector<float> &error_per_cell;
```

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

AdvectionProblem class implementation

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

```
template <int dim>
AdvectionProblem<dim>::AdvectionProblem() : dof_handler(triangulation), fe(1)
{}
template <int dim>
AdvectionProblem<dim>:: AdvectionProblem()
{
    dof_handler.clear();
}
template <int dim>
void AdvectionProblem<dim>::setup_system()
{
    dof_handler.distribute_dofs(fe);
    hanging_node_constraints.clear();
    DoFTools::make_hanging_node_constraints(dof_handler,
                                            hanging_node_constraints);
    hanging_node_constraints.close();
    DynamicSparsityPattern dsp(dof_handler.n_dofs(), dof_handler.n_dofs());
    DoFTools::make_sparsity_pattern(dof_handler, dsp, hanging_node_constraints,
                                    / *keep_constrained_dofs = * / true);
    sparsity_pattern.copy_from(dsp);
    system_matrix.reinit(sparsity_pattern);
    solution.reinit(dof_handler.n_dofs());
    system_rhs.reinit(dof_handler.n_dofs());
}
```

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

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

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

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

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

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

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

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

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

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

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

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

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

Then we define some abbreviations to avoid unnecessarily long lines:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Assert that the system be symmetric.

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

Make a copy of the rhs to use with Ginkgo.

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

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

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

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

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

Setup Ginkgo's data structures

```
auto b = vec::create(exec, gko::dim<2>(num_rows, 1),
                     val_array::view(exec, num_rows, rhs.data()), 1);
auto x = vec::create(exec, gko::dim<2>(num_rows, 1));
auto A = mtx::create(exec, gko::dim<2>(num_rows),
```

```
                    system_matrix.n_nonzero_elements());
mtx::value_type *values = A->get_values();
mtx::index_type *row_ptr = A->get_row_ptrs();
mtx::index_type *col_idx = A->get_col_idxs();
```

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

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

write entry into the first free one for this row

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

then move pointer ahead

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

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

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

Solve system

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

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

```
std::copy(x->get_values(), x->get_values() + num_rows, solution.begin());
/ ************************************************
 * deal.ii internal solver. Here for reference.
 SolverControl           solver_control (1000, 1e-12);
 SolverBicgstab<>        bicgstab (solver_control);
 PreconditionJacobi<> preconditioner;
 preconditioner.initialize(system_matrix, 1.0);
 bicgstab.solve (system_matrix, solution, system_rhs,
                 preconditioner);
************************************************* /
```

Give the solution back to deall.ii

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

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

```
template <int dim>
void AdvectionProblem<dim>::refine_grid()
{
    Vector<float> estimated_error_per_cell(triangulation.n_active_cells());
    GradientEstimation::estimate(dof_handler, solution,
                                 estimated_error_per_cell);
    GridRefinement::refine_and_coarsen_fixed_number(
        triangulation, estimated_error_per_cell, 0.5, 0.03);
    triangulation.execute_coarsening_and_refinement();
}
```

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

```
template <int dim>
```

```
void AdvectionProblem<dim>::output_results(const unsigned int cycle) const
{
    {
        GridOut grid_out;
        std::ofstream output("grid-" + std::to_string(cycle) + ".eps");
        grid_out.write_eps(triangulation, output);
    }
    {
        DataOut<dim> data_out;
        data_out.attach_dof_handler(dof_handler);
        data_out.add_data_vector(solution, "solution");
        data_out.build_patches();
        std::ofstream output("solution-" + std::to_string(cycle) + ".vtk");
        data_out.write_vtk(output);
    }
}
```

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

```
template <int dim>
void AdvectionProblem<dim>::run()
{
    for (unsigned int cycle = 0; cycle < 6; ++cycle) {
        std::cout « "Cycle " « cycle « ':' « std::endl;
        if (cycle == 0) {
            GridGenerator::hyper_cube(triangulation, -1, 1);
            triangulation.refine_global(4);
        } else {
            refine_grid();
        }
        std::cout « "   Number of active cells:       "
                  « triangulation.n_active_cells() « std::endl;
        setup_system();
        std::cout « "   Number of degrees of freedom: " « dof_handler.n_dofs()
                  « std::endl;
        assemble_system();
        solve();
        output_results(cycle);
    }
}
```

GradientEstimation class implementation

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

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

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

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

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

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

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

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

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

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

Now for the details:

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

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

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

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

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

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

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

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

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

Now before going on first compute a list of all active neighbors of the present cell. We do so by first looping over all faces and see whether the neighbor there is active, which would be the case if it is on the same level as the present

cell or one level coarser (note that a neighbor can only be once coarser than the present cell, as we only allow a maximal difference of one refinement over a face in deal.II). Alternatively, the neighbor could be on the same level and be further refined; then we have to find which of its children are next to the present cell and select these (note that if a child of a neighbor of an active cell that is next to this active cell, needs necessarily be active itself, due to the one-refinement rule cited above).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

OK, now that we have all the neighbors, lets start the computation on each of them. First we do some preliminaries: find out about the center of the present cell and the solution at this point. The latter is obtained as a vector of

function values at the quadrature points, of which there are only one, of course. Likewise, the position of the center is the position of the first (and only) quadrature point in real space.

```
const Point<dim> this_center =
    scratch_data.fe_midpoint_value.quadrature_point(0);
std::vector<double> this_midpoint_value(1);
scratch_data.fe_midpoint_value.get_function_values(scratch_data.solution,
                                                   this_midpoint_value);
```

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

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

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

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

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

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

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

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

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

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

... and update the sum of difference quotients:

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

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

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

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

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

```
const Tensor<2, dim> Y_inverse = invert(Y);
Tensor<1, dim> gradient = Y_inverse * projected_gradient;
```

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

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

Main function

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

```
int main()
{
    try {
        dealii::MultithreadInfo::set_thread_limit();
        Step9::AdvectionProblem<2> advection_problem_2d;
        advection_problem_2d.run();
    } catch (std::exception &exc) {
        std::cerr « std::endl
                  « std::endl
                  « "----------------------------------------------------"
                  « std::endl;
        std::cerr « "Exception on processing: " « std::endl
                  « exc.what() « std::endl
                  « "Aborting!" « std::endl
                  « "----------------------------------------------------"
                  « std::endl;
        return 1;
    } catch (...) {
        std::cerr « std::endl
                  « std::endl
                  « "----------------------------------------------------"
                  « std::endl;
        std::cerr « "Unknown exception!" « std::endl
                  « "Aborting!" « std::endl
                  « "----------------------------------------------------"
                  « std::endl;
        return 1;
    }
    return 0;
}
```

Results

Comments about programming and debugging

The plain program

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

 *
 * Author: Wolfgang Bangerth, University of Heidelberg, 2000
 */
/* ---------------------------------------------------------------------
 *
 * This file has been taken verbatim from the deal.ii (version 9.0)
 * examples directory and modified.
 *
 * This example aims to demonstrate the ease with which Ginkgo can
 * be interfaced with other libraries. The only modification/ addition
 * has been to the AdvectionProblem::solve () function.
 *
```

```
 */
#include <deal.II/base/function.h>
#include <deal.II/base/logstream.h>
#include <deal.II/base/quadrature_lib.h>
#include <deal.II/dofs/dof_accessor.h>
#include <deal.II/dofs/dof_handler.h>
#include <deal.II/dofs/dof_tools.h>
#include <deal.II/fe/fe_q.h>
#include <deal.II/fe/fe_values.h>
#include <deal.II/grid/grid_generator.h>
#include <deal.II/grid/grid_out.h>
#include <deal.II/grid/grid_refinement.h>
#include <deal.II/grid/tria.h>
#include <deal.II/grid/tria_accessor.h>
#include <deal.II/grid/tria_iterator.h>
#include <deal.II/lac/constraint_matrix.h>
#include <deal.II/lac/dynamic_sparsity_pattern.h>
#include <deal.II/lac/full_matrix.h>
#include <deal.II/lac/precondition.h>
#include <deal.II/lac/solver_bicgstab.h>
#include <deal.II/lac/sparse_matrix.h>
#include <deal.II/lac/vector.h>
#include <deal.II/numerics/data_out.h>
#include <deal.II/numerics/matrix_tools.h>
#include <deal.II/numerics/vector_tools.h>
#include <deal.II/base/multithread_info.h>
#include <deal.II/base/work_stream.h>
#include <deal.II/base/tensor_function.h>
#include <deal.II/numerics/error_estimator.h>
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
namespace Step9 {
using namespace dealii;
template <int dim>
class AdvectionProblem {
public:
    AdvectionProblem();
     AdvectionProblem();
    void run();
private:
    void setup_system();
    struct AssemblyScratchData {
        AssemblyScratchData(const FiniteElement<dim> &fe);
        AssemblyScratchData(const AssemblyScratchData &scratch_data);
        FEValues<dim> fe_values;
        FEFaceValues<dim> fe_face_values;
    };
    struct AssemblyCopyData {
        FullMatrix<double> cell_matrix;
        Vector<double> cell_rhs;
        std::vector<types::global_dof_index> local_dof_indices;
    };
    void assemble_system();
    void local_assemble_system(
        const typename DoFHandler<dim>::active_cell_iterator &cell,
        AssemblyScratchData &scratch, AssemblyCopyData &copy_data);
    void copy_local_to_global(const AssemblyCopyData &copy_data);
    void solve();
    void refine_grid();
    void output_results(const unsigned int cycle) const;
    Triangulation<dim> triangulation;
    DoFHandler<dim> dof_handler;
    FE_Q<dim> fe;
    ConstraintMatrix hanging_node_constraints;
    SparsityPattern sparsity_pattern;
    SparseMatrix<double> system_matrix;
    Vector<double> solution;
    Vector<double> system_rhs;
};
template <int dim>
class AdvectionField : public TensorFunction<1, dim> {
public:
    AdvectionField() : TensorFunction<1, dim>() {}
    virtual Tensor<1, dim> value(const Point<dim> &p) const;
    virtual void value_list(const std::vector<Point<dim» &points,
                            std::vector<Tensor<1, dim» &values) const;
    DeclException2(ExcDimensionMismatch, unsigned int, unsigned int,
                   « "The vector has size " « arg1 « " but should have "
                   « arg2 « " elements.");
};
template <int dim>
Tensor<1, dim> AdvectionField<dim>::value(const Point<dim> &p) const
{
    Point<dim> value;
    value[0] = 2;
    for (unsigned int i = 1; i < dim; ++i)
```

```
        value[i] = 1 + 0.8 * std::sin(8 * numbers::PI * p[0]);
    return value;
}
template <int dim>
void AdvectionField<dim>::value_list(const std::vector<Point<dim> &points,
                                     std::vector<Tensor<1, dim> &values) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = AdvectionField<dim>::value(points[i]);
}
template <int dim>
class RightHandSide : public Function<dim> {
public:
    RightHandSide() : Function<dim>() {}
    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;
    virtual void value_list(const std::vector<Point<dim> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
private:
    static const Point<dim> center_point;
};
template <>
const Point<1> RightHandSide<1>::center_point = Point<1>(-0.75);
template <>
const Point<2> RightHandSide<2>::center_point = Point<2>(-0.75, -0.75);
template <>
const Point<3> RightHandSide<3>::center_point = Point<3>(-0.75, -0.75, -0.75);
template <int dim>
double RightHandSide<dim>::value(const Point<dim> &p,
                                 const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double diameter = 0.1;
    return ((p - center_point).norm_square() < diameter * diameter
                ? .1 / std::pow(diameter, dim)
                : 0);
}
template <int dim>
void RightHandSide<dim>::value_list(const std::vector<Point<dim> &points,
                                    std::vector<double> &values,
                                    const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = RightHandSide<dim>::value(points[i], component);
}
template <int dim>
class BoundaryValues : public Function<dim> {
public:
    BoundaryValues() : Function<dim>() {}
    virtual double value(const Point<dim> &p,
                         const unsigned int component = 0) const;
    virtual void value_list(const std::vector<Point<dim> &points,
                            std::vector<double> &values,
                            const unsigned int component = 0) const;
};
template <int dim>
double BoundaryValues<dim>::value(const Point<dim> &p,
                                  const unsigned int component) const
{
    (void)component;
    Assert(component == 0, ExcIndexRange(component, 0, 1));
    const double sine_term =
        std::sin(16 * numbers::PI * std::sqrt(p.norm_square()));
    const double weight = std::exp(-5 * p.norm_square()) / std::exp(-5.);
    return sine_term * weight;
}
template <int dim>
void BoundaryValues<dim>::value_list(const std::vector<Point<dim> &points,
                                     std::vector<double> &values,
                                     const unsigned int component) const
{
    Assert(values.size() == points.size(),
           ExcDimensionMismatch(values.size(), points.size()));
    for (unsigned int i = 0; i < points.size(); ++i)
        values[i] = BoundaryValues<dim>::value(points[i], component);
}
class GradientEstimation {
public:
    template <int dim>
    static void estimate(const DoFHandler<dim> &dof,
                         const Vector<double> &solution,
```

```
                        Vector<float> &error_per_cell);
    DeclException2(ExcInvalidVectorLength, int, int,
                   « "Vector has length " « arg1 « ", but should have "
                   « arg2);
    DeclException0(ExcInsufficientDirections);
private:
    template <int dim>
    struct EstimateScratchData {
        EstimateScratchData(const FiniteElement<dim> &fe,
                            const Vector<double> &solution,
                            Vector<float> &error_per_cell);
        EstimateScratchData(const EstimateScratchData &data);
        FEValues<dim> fe_midpoint_value;
        const Vector<double> &solution;
        Vector<float> &error_per_cell;
    };
    struct EstimateCopyData {};
    template <int dim>
    static void estimate_cell(
        const typename DoFHandler<dim>::active_cell_iterator &cell,
        EstimateScratchData<dim> &scratch_data,
        const EstimateCopyData &copy_data);
};
template <int dim>
AdvectionProblem<dim>::AdvectionProblem() : dof_handler(triangulation), fe(1)
{}
template <int dim>
AdvectionProblem<dim>:: AdvectionProblem()
{
    dof_handler.clear();
}
template <int dim>
void AdvectionProblem<dim>::setup_system()
{
    dof_handler.distribute_dofs(fe);
    hanging_node_constraints.clear();
    DoFTools::make_hanging_node_constraints(dof_handler,
                                            hanging_node_constraints);
    hanging_node_constraints.close();
    DynamicSparsityPattern dsp(dof_handler.n_dofs(), dof_handler.n_dofs());
    DoFTools::make_sparsity_pattern(dof_handler, dsp, hanging_node_constraints,
                                    /*keep_constrained_dofs = */ true);
    sparsity_pattern.copy_from(dsp);
    system_matrix.reinit(sparsity_pattern);
    solution.reinit(dof_handler.n_dofs());
    system_rhs.reinit(dof_handler.n_dofs());
}
template <int dim>
void AdvectionProblem<dim>::assemble_system()
{
    WorkStream::run(dof_handler.begin_active(), dof_handler.end(), *this,
                    &AdvectionProblem::local_assemble_system,
                    &AdvectionProblem::copy_local_to_global,
                    AssemblyScratchData(fe), AssemblyCopyData());
    hanging_node_constraints.condense(system_matrix);
    hanging_node_constraints.condense(system_rhs);
}
template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const FiniteElement<dim> &fe)
    : fe_values(fe, QGauss<dim>(2),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(fe, QGauss<dim - 1>(2),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}
template <int dim>
AdvectionProblem<dim>::AssemblyScratchData::AssemblyScratchData(
    const AssemblyScratchData &scratch_data)
    : fe_values(scratch_data.fe_values.get_fe(),
                scratch_data.fe_values.get_quadrature(),
                update_values | update_gradients | update_quadrature_points |
                    update_JxW_values),
      fe_face_values(scratch_data.fe_face_values.get_fe(),
                     scratch_data.fe_face_values.get_quadrature(),
                     update_values | update_quadrature_points |
                         update_JxW_values | update_normal_vectors)
{}
template <int dim>
void AdvectionProblem<dim>::local_assemble_system(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    AssemblyScratchData &scratch_data, AssemblyCopyData &copy_data)
{
    const AdvectionField<dim> advection_field;
    const RightHandSide<dim> right_hand_side;
    const BoundaryValues<dim> boundary_values;
```

```
    const unsigned int dofs_per_cell = fe.dofs_per_cell;
    const unsigned int n_q_points =
        scratch_data.fe_values.get_quadrature().size();
    const unsigned int n_face_q_points =
        scratch_data.fe_face_values.get_quadrature().size();
    copy_data.cell_matrix.reinit(dofs_per_cell, dofs_per_cell);
    copy_data.cell_rhs.reinit(dofs_per_cell);
    copy_data.local_dof_indices.resize(dofs_per_cell);
    std::vector<double> rhs_values(n_q_points);
    std::vector<Tensor<1, dim» advection_directions(n_q_points);
    std::vector<double> face_boundary_values(n_face_q_points);
    std::vector<Tensor<1, dim» face_advection_directions(n_face_q_points);
    scratch_data.fe_values.reinit(cell);
    advection_field.value_list(scratch_data.fe_values.get_quadrature_points(),
                               advection_directions);
    right_hand_side.value_list(scratch_data.fe_values.get_quadrature_points(),
                               rhs_values);
    const double delta = 0.1 * cell->diameter();
    for (unsigned int q_point = 0; q_point < n_q_points; ++q_point)
        for (unsigned int i = 0; i < dofs_per_cell; ++i) {
            for (unsigned int j = 0; j < dofs_per_cell; ++j)
                copy_data.cell_matrix(i, j) +=
                    ((advection_directions[q_point] *
                      scratch_data.fe_values.shape_grad(j, q_point) *
                      (scratch_data.fe_values.shape_value(i, q_point) +
                       delta *
                           (advection_directions[q_point] *
                            scratch_data.fe_values.shape_grad(i, q_point)))) *
                     scratch_data.fe_values.JxW(q_point));
            copy_data.cell_rhs(i) +=
                ((scratch_data.fe_values.shape_value(i, q_point) +
                  delta * (advection_directions[q_point] *
                           scratch_data.fe_values.shape_grad(i, q_point))) *
                 rhs_values[q_point] * scratch_data.fe_values.JxW(q_point));
        }
    for (unsigned int face = 0; face < GeometryInfo<dim>::faces_per_cell;
         ++face)
        if (cell->face(face)->at_boundary()) {
            scratch_data.fe_face_values.reinit(cell, face);
            boundary_values.value_list(
                scratch_data.fe_face_values.get_quadrature_points(),
                face_boundary_values);
            advection_field.value_list(
                scratch_data.fe_face_values.get_quadrature_points(),
                face_advection_directions);
            for (unsigned int q_point = 0; q_point < n_face_q_points; ++q_point)
                if (scratch_data.fe_face_values.normal_vector(q_point) *
                        face_advection_directions[q_point] <
                    0)
                    for (unsigned int i = 0; i < dofs_per_cell; ++i) {
                        for (unsigned int j = 0; j < dofs_per_cell; ++j)
                            copy_data.cell_matrix(i, j) -=
                                (face_advection_directions[q_point] *
                                 scratch_data.fe_face_values.normal_vector(
                                     q_point) *
                                 scratch_data.fe_face_values.shape_value(
                                     i, q_point) *
                                 scratch_data.fe_face_values.shape_value(
                                     j, q_point) *
                                 scratch_data.fe_face_values.JxW(q_point));
                        copy_data.cell_rhs(i) -=
                            (face_advection_directions[q_point] *
                             scratch_data.fe_face_values.normal_vector(
                                 q_point) *
                             face_boundary_values[q_point] *
                             scratch_data.fe_face_values.shape_value(i,
                                                                     q_point) *
                             scratch_data.fe_face_values.JxW(q_point));
                    }
        }
    cell->get_dof_indices(copy_data.local_dof_indices);
}
template <int dim>
void AdvectionProblem<dim>::copy_local_to_global(
    const AssemblyCopyData &copy_data)
{
    for (unsigned int i = 0; i < copy_data.local_dof_indices.size(); ++i) {
        for (unsigned int j = 0; j < copy_data.local_dof_indices.size(); ++j)
            system_matrix.add(copy_data.local_dof_indices[i],
                              copy_data.local_dof_indices[j],
                              copy_data.cell_matrix(i, j));
        system_rhs(copy_data.local_dof_indices[i]) += copy_data.cell_rhs(i);
    }
}
template <int dim>
void AdvectionProblem<dim>::solve()
{
```

```
    Assert(system_matrix.m() == system_matrix.n(), ExcNotQuadratic());
    auto num_rows = system_matrix.m();
    std::vector<double> rhs(num_rows);
    std::copy(system_rhs.begin(), system_rhs.begin() + num_rows, rhs.begin());
    using vec = gko::matrix::Dense<>;
    using mtx = gko::matrix::Csr<>;
    using bicgstab = gko::solver::Bicgstab<>;
    using bj = gko::preconditioner::Jacobi<>;
    using val_array = gko::Array<double>;
    std::shared_ptr<gko::Executor> exec = gko::ReferenceExecutor::create();
    auto b = vec::create(exec, gko::dim<2>(num_rows, 1),
                         val_array::view(exec, num_rows, rhs.data()), 1);
    auto x = vec::create(exec, gko::dim<2>(num_rows, 1));
    auto A = mtx::create(exec, gko::dim<2>(num_rows),
                         system_matrix.n_nonzero_elements());
    mtx::value_type *values = A->get_values();
    mtx::index_type *row_ptr = A->get_row_ptrs();
    mtx::index_type *col_idx = A->get_col_idxs();
    row_ptr[0] = 0;
    for (auto row = 1; row <= num_rows; ++row) {
        row_ptr[row] = row_ptr[row - 1] + system_matrix.get_row_length(row - 1);
    }
    std::vector<mtx::index_type> ptrs(num_rows + 1);
    std::copy(A->get_row_ptrs(), A->get_row_ptrs() + num_rows + 1,
              ptrs.begin());
    for (auto row = 0; row < system_matrix.m(); ++row) {
        for (auto p = system_matrix.begin(row); p != system_matrix.end(row);
             ++p) {
            col_idx[ptrs[row]] = p->column();
            values[ptrs[row]] = p->value();
            ++ptrs[row];
        }
    }
    auto solver_gen =
        bicgstab::build()
            .with_criteria(
                gko::stop::Iteration::build().with_max_iters(1000).on(exec),
                gko::stop::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-12)
                    .on(exec))
            .with_preconditioner(bj::build().on(exec))
            .on(exec);
    auto solver = solver_gen->generate(gko::give(A));
    solver->apply(gko::lend(b), gko::lend(x));
    std::copy(x->get_values(), x->get_values() + num_rows, solution.begin());
    /*************************************************
     * deal.ii internal solver. Here for reference.
     SolverControl           solver_control (1000, 1e-12);
     SolverBicgstab<>        bicgstab (solver_control);

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

     bicgstab.solve (system_matrix, solution, system_rhs,
                     preconditioner);
    *************************************************/
    hanging_node_constraints.distribute(solution);
}
template <int dim>
void AdvectionProblem<dim>::refine_grid()
{
    Vector<float> estimated_error_per_cell(triangulation.n_active_cells());
    GradientEstimation::estimate(dof_handler, solution,
                                 estimated_error_per_cell);
    GridRefinement::refine_and_coarsen_fixed_number(
        triangulation, estimated_error_per_cell, 0.5, 0.03);
    triangulation.execute_coarsening_and_refinement();
}
template <int dim>
void AdvectionProblem<dim>::output_results(const unsigned int cycle) const
{
    {
        GridOut grid_out;
        std::ofstream output("grid-" + std::to_string(cycle) + ".eps");
        grid_out.write_eps(triangulation, output);
    }
    {
        DataOut<dim> data_out;
        data_out.attach_dof_handler(dof_handler);
        data_out.add_data_vector(solution, "solution");
        data_out.build_patches();
        std::ofstream output("solution-" + std::to_string(cycle) + ".vtk");
        data_out.write_vtk(output);
    }
}
template <int dim>
void AdvectionProblem<dim>::run()
```

```
{
    for (unsigned int cycle = 0; cycle < 6; ++cycle) {
        std::cout « "Cycle " « cycle « ':' « std::endl;
        if (cycle == 0) {
            GridGenerator::hyper_cube(triangulation, -1, 1);
            triangulation.refine_global(4);
        } else {
            refine_grid();
        }
        std::cout « "   Number of active cells:       "
                  « triangulation.n_active_cells() « std::endl;
        setup_system();
        std::cout « "   Number of degrees of freedom: " « dof_handler.n_dofs()
                  « std::endl;
        assemble_system();
        solve();
        output_results(cycle);
    }
}
template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const FiniteElement<dim> &fe, const Vector<double> &solution,
    Vector<float> &error_per_cell)
    : fe_midpoint_value(fe, QMidpoint<dim>(),
                        update_values | update_quadrature_points),
      solution(solution),
      error_per_cell(error_per_cell)
{}
template <int dim>
GradientEstimation::EstimateScratchData<dim>::EstimateScratchData(
    const EstimateScratchData &scratch_data)
    : fe_midpoint_value(scratch_data.fe_midpoint_value.get_fe(),
                        scratch_data.fe_midpoint_value.get_quadrature(),
                        update_values | update_quadrature_points),
      solution(scratch_data.solution),
      error_per_cell(scratch_data.error_per_cell)
{}
template <int dim>
void GradientEstimation::estimate(const DoFHandler<dim> &dof_handler,
                                  const Vector<double> &solution,
                                  Vector<float> &error_per_cell)
{
    Assert(error_per_cell.size() ==
               dof_handler.get_triangulation().n_active_cells(),
           ExcInvalidVectorLength(
               error_per_cell.size(),
               dof_handler.get_triangulation().n_active_cells()));
    WorkStream::run(dof_handler.begin_active(), dof_handler.end(),
                    &GradientEstimation::template estimate_cell<dim>,
                    std::function<void(const EstimateCopyData &)>(),
                    EstimateScratchData<dim>(dof_handler.get_fe(), solution,
                                             error_per_cell),
                    EstimateCopyData());
}
template <int dim>
void GradientEstimation::estimate_cell(
    const typename DoFHandler<dim>::active_cell_iterator &cell,
    EstimateScratchData<dim> &scratch_data, const EstimateCopyData &)
{
    Tensor<2, dim> Y;
    std::vector<typename DoFHandler<dim>::active_cell_iterator>
        active_neighbors;
    active_neighbors.reserve(GeometryInfo<dim>::faces_per_cell *
                             GeometryInfo<dim>::max_children_per_face);
    scratch_data.fe_midpoint_value.reinit(cell);
    Tensor<1, dim> projected_gradient;
    active_neighbors.clear();
    for (unsigned int face_no = 0; face_no < GeometryInfo<dim>::faces_per_cell;
         ++face_no)
        if (!cell->at_boundary(face_no)) {
            const typename DoFHandler<dim>::face_iterator face =
                cell->face(face_no);
            const typename DoFHandler<dim>::cell_iterator neighbor =
                cell->neighbor(face_no);
            if (neighbor->active())
                active_neighbors.push_back(neighbor);
            else {
                if (dim == 1) {
                    typename DoFHandler<dim>::cell_iterator neighbor_child =
                        neighbor;
                    while (neighbor_child->has_children())
                        neighbor_child =
                            neighbor_child->child(face_no == 0 ? 1 : 0);
                    Assert(
                        neighbor_child->neighbor(face_no == 0 ? 1 : 0) == cell,
                        ExcInternalError());
                    active_neighbors.push_back(neighbor_child);
```

```
                } else
                    for (unsigned int subface_no = 0;
                         subface_no < face->n_children(); ++subface_no)
                        active_neighbors.push_back(
                            cell->neighbor_child_on_subface(face_no,
                                                            subface_no));
            }
        }
    const Point<dim> this_center =
        scratch_data.fe_midpoint_value.quadrature_point(0);
    std::vector<double> this_midpoint_value(1);
    scratch_data.fe_midpoint_value.get_function_values(scratch_data.solution,
                                                       this_midpoint_value);
    std::vector<double> neighbor_midpoint_value(1);
    typename std::vector<typename DoFHandler<dim>::active_cell_iterator>::
        const_iterator neighbor_ptr = active_neighbors.begin();
    for (; neighbor_ptr != active_neighbors.end(); ++neighbor_ptr) {
        const typename DoFHandler<dim>::active_cell_iterator neighbor =
            *neighbor_ptr;
        scratch_data.fe_midpoint_value.reinit(neighbor);
        const Point<dim> neighbor_center =
            scratch_data.fe_midpoint_value.quadrature_point(0);
        scratch_data.fe_midpoint_value.get_function_values(
            scratch_data.solution, neighbor_midpoint_value);
        Tensor<1, dim> y = neighbor_center - this_center;
        const double distance = y.norm();
        y /= distance;
        for (unsigned int i = 0; i < dim; ++i)
            for (unsigned int j = 0; j < dim; ++j) Y[i][j] += y[i] * y[j];
        projected_gradient +=
            (neighbor_midpoint_value[0] - this_midpoint_value[0]) / distance *
            y;
    }
    AssertThrow(determinant(Y) != 0, ExcInsufficientDirections());
    const Tensor<2, dim> Y_inverse = invert(Y);
    Tensor<1, dim> gradient = Y_inverse * projected_gradient;
    scratch_data.error_per_cell(cell->active_cell_index()) =
        (std::pow(cell->diameter(), 1 + 1.0 * dim / 2) *
         std::sqrt(gradient.norm_square()));
}
}  // namespace Step9
int main()
{
    try {
        dealii::MultithreadInfo::set_thread_limit();
        Step9::AdvectionProblem<2> advection_problem_2d;
        advection_problem_2d.run();
    } catch (std::exception &exc) {
        std::cerr << std::endl
                  << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        std::cerr << "Exception on processing: " << std::endl
                  << exc.what() << std::endl
                  << "Aborting!" << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        return 1;
    } catch (...) {
        std::cerr << std::endl
                  << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        std::cerr << "Unknown exception!" << std::endl
                  << "Aborting!" << std::endl
                  << "----------------------------------------------------"
                  << std::endl;
        return 1;
    }
    return 0;
}
```

Chapter 13

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 1.62987 seconds.
    Average library overhead:     1629.87 [nanoseconds / iteration]
```

Comments about programming and debugging

The plain program

```
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*****************************<GINKGO LICENSE>******************************/
#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 14

The ginkgo-ranges program

The ranges and accessor example..

Introduction

About the example

The commented program

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

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

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

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

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

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

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

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

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

a utility function for printing the factorization on screen

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

```
    for (int i = 0; i < A.length(0); ++i) {
        std::cout « "\n  ";
        for (int j = 0; j < A.length(1); ++j) {
            std::cout « (i <= j ? A(i, j) : 0.) « " ";
        }
    }
    std::cout « "\n]" « std::endl;
}
int main(int argc, char *argv[])
{
    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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*****************************<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 15

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 <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;
```

Figure out where to run the code

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

```
            gko::HipExecutor::get_num_devices() > 0) {
    exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
} else {
    std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
    std::exit(-1);
}
```

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::ResidualNormReduction<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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#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
        std::exit(-1);
    }
    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::ResidualNormReduction<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 16

The inverse-iteration program

The inverse iteration example..

This example depends on simple-solver, .

Introduction

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

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

About the example

The commented program

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

Some shortcuts

```
using precision = std::complex<double>;
using real_precision = 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

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

linear system solver parameters

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

eigensolver parameters

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

Read data

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

Generate shifted matrix A - zI

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

```
auto one = share(gko::initialize<vec>({precision{1.0}}, exec));
auto neg_one = share(gko::initialize<vec>({-precision{1.0}}, exec));
auto neg_z = gko::initialize<vec>({-z}, exec);
auto system_matrix = share(gko::Combination<precision>::create(
    one, A, gko::initialize<vec>({-z}, exec),
    gko::matrix::Identity<precision>::create(exec, A->get_size()[0])));
```

Generate solver operator (A - zI)^-1

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

inverse iterations

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

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

(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 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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#include <ginkgo/ginkgo.hpp>
#include <cmath>
#include <complex>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>
int main(int argc, char *argv[])
{
    using precision = std::complex<double>;
    using real_precision = 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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    auto this_exec = exec->get_master();
    auto system_max_iterations = 100u;
    auto system_residual_goal = real_precision{1e-16};
    auto max_iterations = 20u;
    auto residual_goal = real_precision{1e-8};
    auto z = precision{20.0, 2.0};
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto one = share(gko::initialize<vec>({precision{1.0}}, exec));
    auto neg_one = share(gko::initialize<vec>({-precision{1.0}}, exec));
    auto neg_z = gko::initialize<vec>({-z}, exec);
    auto system_matrix = share(gko::Combination<precision>::create(
        one, A, gko::initialize<vec>({-z}, exec),
        gko::matrix::Identity<precision>::create(exec, A->get_size()[0])));
    auto solver =
        solver_type::build()
```

```
            .with_criteria(gko::stop::Iteration::build()
                               .with_max_iters(system_max_iterations)
                               .on(exec),
                           gko::stop::ResidualNormReduction<precision>::build()
                               .with_reduction_factor(system_residual_goal)
                               .on(exec))
            .on(exec)
            ->generate(system_matrix);
    auto x = [&] {
        auto work = vec::create(this_exec, gko::dim<2>{A->get_size()[0], 1});
        const auto n = work->get_size()[0];
        for (int i = 0; i < n; ++i) {
            work->get_values()[i] = precision{1.0} / sqrt(n);
        }
        return clone(exec, work);
    }();
    auto y = clone(x);
    auto tmp = clone(x);
    auto norm = 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 17

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 <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 and how many block-Jacobi sweeps to use

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
} else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
} else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "hip" &&
           gko::HipExecutor::get_num_devices() > 0) {
    exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
} else {
    std::cerr « "Usage: " « argv[0] « " [executor] [sweeps]"
              « std::endl;
    std::exit(-1);
}
unsigned int sweeps = (argc == 3) ? atoi(argv[2]) : 5u;
```

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::ParIlu<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::Ilu<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::ResidualNormReduction<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()) / 100000000.0 « "\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]: 3.89406
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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#include <ginkgo/ginkgo.hpp>
#include <cstdlib>
#include <fstream>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if ((argc == 2 || argc == 3) && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor] [sweeps]"
                  << std::endl;
        std::exit(-1);
    }
    unsigned int sweeps = (argc == 3) ? atoi(argv[2]) : 5u;
    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::ResidualNormReduction<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()) / 100000000.0 « "\n";
    std::cout « "Residual norm sqrt(r^T r): \n";
    write(std::cout, gko::lend(res));
}
```

Chapter 18

The iterative-refinement program

The iterative refinement solver example..

This example depends on simple-solver.

This example shows how to use the iterative refinement 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 is used as the inner solver to an iterative refinement (IR) method which solves a linear system. The example features the iteration count and runtime of the IR solver.

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#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 ir = gko::solver::Ir<ValueType>;
```

Print version information

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

Figure out where to run the code

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

```
    std::exit(-1);
}
```

Read data

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

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::ResidualNormReduction<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::ResidualNormReduction<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]: 14.9084
```

Comments about programming and debugging

The plain program

```
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*******************************<GINKGO LICENSE>******************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
```

```
    }
    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::ResidualNormReduction<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::ResidualNormReduction<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 19

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::ResidualNormReduction<>::build()
                .with_reduction_factor(1e-15)
                .on(gpu))
        .on(gpu);
```

Solve system

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

Write result

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

Results

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

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

Comments about programming and debugging

The plain program

```
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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::ResidualNormReduction<>::build()
                    .with_reduction_factor(1e-15)
                    .on(gpu))
            .on(gpu);
    solver->generate(give(A))->apply(lend(b), lend(x));
    write(std::cout, lend(x));
}
```

Chapter 20

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 <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

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
```

```
    exec = gko::OmpExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
} else if (argc == 2 && std::string(argv[1]) == "hip" &&
           gko::HipExecutor::get_num_devices() > 0) {
    exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
} else {
    std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
    std::exit(-1);
}
```

Read data

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

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::ResidualNormReduction<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 ∗ inner_solution = 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 + 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]: 14.2256
```

Comments about programming and debugging

The plain program

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*****************************<GINKGO LICENSE>*****************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    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::ResidualNormReduction<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 21

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:

[\Omega = (0,1)^2 \ \Omega_b = [0,1]^2 \text{ (with boundary)} \ \partial\Omega = \Omega_b \backslash \Omega \ u : \Omega_b -> R \ u'' = f \in \Omega \ u = u_D \in \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), \ldots, (xk,y1),(x1,y2), \ldots, (xk,yk,z1)) 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}^(1,0) stencil(a,b) * u_{(i+a,j+b} = -f_k h^2 - \sum_{a=-1}^1 stencil(a,1) * u_{(i+a,j+1}]

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

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

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

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 -> R
    u" = f in \Omega
    u = u_D on \partial\Omega
using a finite difference method on an equidistant grid with `K` discretization
points (`K` can be controlled with a command line parameter). The discretization
may be done by any order Taylor polynomial.
For an equidistant grid with K "inner" discretization points (x1,y1), ...,
(xk,y1),(x1,y2), ..., (xk,yk) step size h = 1 / (K + 1) and a stencil \in
\R^{3 x 3}, the formula produces a system of linear equations
\sum_{a,b=-1}^1 stencil(a,b) * u_{(i+a,j+b} = -f_k h^2,  on any inner node with
a neighborhood of inner nodes
On any node, where neighbor is on the border, the neighbor is replaced with a
'-stencil(a,b) * u_{i+a,j+b}' and added to the right hand side vector. For
example a node with a neighborhood of only edge nodes may look like this
\sum_{a,b=-1}^(1,0) stencil(a,b) * u_{(i+a,j+b} = -f_k h^2 - \sum_{a=-1}^1
stencil(a,1) * u_{(i+a,j+1}
which is then solved using Ginkgo's implementation of the CG method
preconditioned with block-Jacobi. It is also possible to specify on which
executor Ginkgo will solve the system via the command line.
The function `f` is set to `f(x,y) = 6x + 6y` (making the solution `u(x,y) = x^3
+ y^3`), but that can be changed in the `main` function. Also the stencil values
for the core, the faces, the edge and the corners can be changed when passing
additional parameters.

The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
****************************<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_idxs, 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 = l + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxs[pos] = index + l + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
```

```
}
```

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

```
template <typename Closure, typename ClosureT, 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_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;
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);
         }},
        {"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 SpMVs to run (in this case `exec`). When creating array views, we have to specify the executor where the data is (in this case `app_exec`).

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

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

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

RHS: similar to matrix

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

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

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

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(
            gko::stop::Iteration::build().with_max_iters(dp_2).on(exec),
            gko::stop::ResidualNormReduction<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[])
{
    if (argc < 2) {
        std::cerr « "Usage: " « argv[0] « " DISCRETIZATION_POINTS [executor]"
                 « " [stencil_alpha] [stencil_beta] [stencil_gamma]"
                 « std::endl;
        std::exit(-1);
    }
    using ValueType = double;
    using IndexType = int;
    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    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> coefs{
    gamma_c, beta_c, gamma_c,
          beta_c, alpha_c, beta_c,
    gamma_c, beta_c, gamma_c};
```

clang-format on

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

problem:

```
auto correct_u = [](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(),
                        coefs.data());
```

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

```
    generate_rhs(dp, f, correct_u, rhs.data(), coefs.data());
    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;
    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 of the relative error at K=10 should be

```
0.00150263 0.00676184 0.0210368 0.0488355 0.0946657 0.163035 0.258452 0.385425 0.54846 0.752066
0.00676184 0.012021 0.026296 0.0540947 0.0999249 0.168295 0.263712 0.390684 0.553719 0.757325
0.0210368 0.026296 0.040571 0.0683697 0.1142 0.18257 0.277987 0.404959 0.567994 0.7716
0.0488354 0.0540947 0.0683697 0.0961683 0.141998 0.210368 0.305785 0.432757 0.595793 0.799399
0.0946656 0.0999248 0.1142 0.141998 0.187829 0.256198 0.351615 0.478588 0.641623 0.845229
0.163035 0.168295 0.182569 0.210368 0.256198 0.324568 0.419985 0.546957 0.709993 0.913599
0.258452 0.263711 0.277987 0.305785 0.351615 0.419985 0.515402 0.642374 0.80541 1.00902
0.385424 0.390684 0.404959 0.432757 0.478588 0.546957 0.642374 0.769346 0.932382 1.13599
0.54846 0.553719 0.567994 0.595793 0.641623 0.709992 0.805409 0.932382 1.09542 1.29902
0.752066 0.757325 0.7716 0.799399 0.845229 0.913599 1.00902 1.13599 1.29902 1.50263
The average relative error is 1.4283e-07
The runtime is 5.784994 ms
```

Comments about programming and debugging

The plain program

```
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*******************************<GINKGO LICENSE>******************************/
/*****************************<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 -> R
    u” = f in \Omega
    u = u_D on \partial\Omega

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

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

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

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

which is then solved using Ginkgo’s implementation of the CG method
```

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

The intention of this is to show how generation of stencil values and the right
hand side vector changes when increasing the dimension.
*****************************<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_idxs, 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 = l + 1 + 3 * (j + 1);
                    if ((k + j) >= 0 && (k + j) < dp && (i + l) >= 0 &&
                        (i + l) < dp) {
                        values[pos] = coefs[offset];
                        col_idxs[pos] = index + l + dp * j;
                        ++pos;
                    }
                }
            }
            row_ptrs[index + 1] = pos;
        }
    }
}
template <typename Closure, typename ClosureT, 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);
             }},
            {"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::ResidualNormReduction<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[])
{
```

```
    if (argc < 2) {
        std::cerr « "Usage: " « argv[0] « " DISCRETIZATION_POINTS [executor]"
                 « " [stencil_alpha] [stencil_beta] [stencil_gamma]"
                 « std::endl;
        std::exit(-1);
    }
    using ValueType = double;
    using IndexType = int;
    const int discretization_points = argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    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;
    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;
}
```

Chapter 22

The papi-logging program

The papi logging example..

This example depends on simple-solver-logging.

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <papi.h>
#include <fstream>
#include <iostream>
#include <string>
#include <thread>
namespace {
void papi_add_event(const std::string &event_name, int &eventset)
{
    int code;
    int ret_val = PAPI_event_name_to_code(event_name.c_str(), &code);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_name_to_code()" « std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_add_event(eventset, code);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_name_to_code()" « std::endl;
        std::exit(-1);
    }
}
template <typename T>
std::string to_string(T *ptr)
{
    std::ostringstream os;
    os « reinterpret_cast<gko::uintptr>(ptr);
    return os.str();
}
}  // namespace
int init_papi_counters(std::string solver_name, std::string A_name)
{
```

Initialize PAPI, add events and start it up

```
    int eventset = PAPI_NULL;
    int ret_val = PAPI_library_init(PAPI_VER_CURRENT);
    if (ret_val != PAPI_VER_CURRENT) {
        std::cerr « "Error at PAPI_library_init()" « std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_create_eventset(&eventset);
```

```
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_create_eventset()" « std::endl;
        std::exit(-1);
    }
    std::string simple_apply_string("sde:::ginkgo0::linop_apply_completed::");
    std::string advanced_apply_string(
        "sde:::ginkgo0::linop_advanced_apply_completed::");
    papi_add_event(simple_apply_string + solver_name, eventset);
    papi_add_event(simple_apply_string + A_name, eventset);
    papi_add_event(advanced_apply_string + A_name, eventset);
    ret_val = PAPI_start(eventset);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_start()" « std::endl;
        std::exit(-1);
    }
    return eventset;
}
void print_papi_counters(int eventset)
{
```

Stop PAPI and read the linop_apply_completed event for all of them

```
long long int values[3];
int ret_val = PAPI_stop(eventset, values);
if (PAPI_OK != ret_val) {
    std::cerr « "Error at PAPI_stop()" « std::endl;
    std::exit(-1);
}
PAPI_shutdown();
```

Print all values returned from PAPI

```
    std::cout « "PAPI SDE counters:" « std::endl;
    std::cout « "solver did " « values[0] « " applies." « std::endl;
    std::cout « "A did " « values[1] « " simple applies." « std::endl;
    std::cout « "A did " « values[2] « " advanced applies." « std::endl;
}
int main(int argc, char *argv[])
{
```

Some shortcuts

```
using 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;
```

Figure out where to run the code

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

Read data

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

Generate solver

```
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::ResidualNormReduction<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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*******************************<GINKGO LICENSE>******************************/
#include <ginkgo/ginkgo.hpp>
#include <papi.h>
#include <fstream>
#include <iostream>
#include <string>
#include <thread>
namespace {
void papi_add_event(const std::string &event_name, int &eventset)
{
    int code;
    int ret_val = PAPI_event_name_to_code(event_name.c_str(), &code);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_name_to_code()" « std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_add_event(eventset, code);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_name_to_code()" « std::endl;
        std::exit(-1);
    }
}
template <typename T>
std::string to_string(T *ptr)
{
    std::ostringstream os;
    os « reinterpret_cast<gko::uintptr>(ptr);
    return os.str();
}
}  // namespace
int init_papi_counters(std::string solver_name, std::string A_name)
{
    int eventset = PAPI_NULL;
    int ret_val = PAPI_library_init(PAPI_VER_CURRENT);
    if (ret_val != PAPI_VER_CURRENT) {
        std::cerr « "Error at PAPI_library_init()" « std::endl;
        std::exit(-1);
    }
    ret_val = PAPI_create_eventset(&eventset);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_create_eventset()" « std::endl;
        std::exit(-1);
    }
    std::string simple_apply_string("sde:::ginkgo0::linop_apply_completed::");
    std::string advanced_apply_string(
        "sde:::ginkgo0::linop_advanced_apply_completed::");
    papi_add_event(simple_apply_string + solver_name, eventset);
    papi_add_event(simple_apply_string + A_name, eventset);
    papi_add_event(advanced_apply_string + A_name, eventset);
    ret_val = PAPI_start(eventset);
```

```
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_start()" « std::endl;
        std::exit(-1);
    }
    return eventset;
}
void print_papi_counters(int eventset)
{
    long long int values[3];
    int ret_val = PAPI_stop(eventset, values);
    if (PAPI_OK != ret_val) {
        std::cerr « "Error at PAPI_stop()" « std::endl;
        std::exit(-1);
    }
    PAPI_shutdown();
    std::cout « "PAPI SDE counters:" « std::endl;
    std::cout « "solver did " « values[0] « " applies." « std::endl;
    std::cout « "A did " « values[1] « " simple applies." « std::endl;
    std::cout « "A did " « values[2] « " advanced applies." « std::endl;
}
int main(int argc, char *argv[])
{
    using 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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
        std::exit(-1);
    }
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
    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::ResidualNormReduction<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 23

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

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::ResidualNormReduction<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 recurent 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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#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<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 {
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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc > 1 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc > 1 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        print_usage(argv[0]);
    }
    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::ResidualNormReduction<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 24

The poisson-solver program

The poisson solver example..

This example depends on simple-solver.

Introduction

This example solves a 1D Poisson equation:

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

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

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

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

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

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

The intention of the example is to show how Ginkgo can be 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_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;
    }
}
```

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

Get number of discretization points

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

Figure out where to run the code

```
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);
         }},
        {"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::ResidualNormReduction<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));
    print_solution<ValueType>(u0, u1, lend(u));
    std::cout « "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:

```
0
0.00010798
0.000863838
0.00291545
0.0069107
0.0134975
0.0233236
0.037037
0.0552856
0.0787172
0.10798
0.143721
0.186589
0.237231
0.296296
0.364431
0.442285
0.530504
0.629738
0.740633
0.863838
1
The average relative error is 1.87318e-15
```

Comments about programming and debugging

The plain program

```
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(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>
#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>;
    if (argc < 2) {
        std::cerr « "Usage: " « argv[0] « " DISCRETIZATION_POINTS [executor]"
                 « std::endl;
        std::exit(-1);
    }
    const unsigned int discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    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);
             }},
            {"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::ResidualNormReduction<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));
    print_solution<ValueType>(u0, u1, lend(u));
    std::cout << "The average relative error is "
              << calculate_error(discretization_points, lend(u), correct_u) /
                     static_cast<gko::remove_complex<ValueType>>(
                         discretization_points)
              << std::endl;
}
```

Chapter 25

The preconditioned-solver program

The preconditioned solver example..

This example depends on simple-solver.

Introduction

About the example

The commented program

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

Some shortcuts

```
using 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;
```

Figure out where to run the code

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

Read data
```
auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
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::ResidualNormReduction<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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*****************************<GINKGO LICENSE>*******************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
    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::ResidualNormReduction<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 26

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 <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());
               }}};
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: " « argv[0]
             « " <reference|omp|cuda|hip> [<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 precond = 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-l");
    output(gko::as<gko::matrix::Csr<>>(ilu->get_operators()[1].get()),
           matrix + ".ilu-u");
} else if (precond == "parilu") {
```

parilu: iterations

```
    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") {
```

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::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") {
```

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> [<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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*****************************<GINKGO LICENSE>*****************************/
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <functional>
#include <iostream>
#include <map>
#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());
               }}};
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: " << argv[0]
                  << " <reference|omp|cuda|hip> [<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 precond = 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::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") {
    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::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");
    }
}
```

Chapter 27

The simple-solver program

The simple solver example..

Introduction

This simple solver example should help you get started with Ginkgo. This example is meant for you to understand how Ginkgo works and how you can solve a simple linear system with Ginkgo. We encourage you to play with the code, change the parameters and see what is best suited for your purposes.

About the example

Each example has the following sections:

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

The commented program

Include files

This is the main ginkgo header file.

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

Add the fstream header to read from data from files.

```
#include <fstream>
```

Add the C++ iostream header to output information to the console.
```
#include <iostream>
```

Add the string manipulation header to handle strings.
```
#include <string>
int main(int argc, char *argv[])
{
```

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

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

Reading your data and transfer to the proper device.

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

Note

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

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

Creating the solver

Generate the gko::solver factory. Ginkgo uses the concept of Factories to build solvers with certain properties. Observe the Fluent interface used here. Here a cg solver is generated with a stopping criteria of maximum iterations of 20 and a residual norm reduction of 1e-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::ResidualNormReduction<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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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 <iostream>
#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;
    std::shared_ptr<gko::Executor> exec;
    if (argc == 1 || std::string(argv[1]) == "reference") {
        exec = gko::ReferenceExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "omp") {
        exec = gko::OmpExecutor::create();
    } else if (argc == 2 && std::string(argv[1]) == "cuda" &&
               gko::CudaExecutor::get_num_devices() > 0) {
        exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
    } else if (argc == 2 && std::string(argv[1]) == "hip" &&
               gko::HipExecutor::get_num_devices() > 0) {
        exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
    } else {
        std::cerr << "Usage: " << argv[0] << " [executor]" << std::endl;
        std::exit(-1);
    }
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
    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::ResidualNormReduction<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 28

The simple-solver-logging program

The simple solver with logging example..

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

Introduction

About the example

The commented program

```
#include <ginkgo/ginkgo.hpp>
#include <fstream>
#include <iomanip>
#include <iostream>
#include <string>
namespace {
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;
```

Figure out where to run the code

```
std::shared_ptr<gko::Executor> exec;
if (argc == 1 || std::string(argv[1]) == "reference") {
    exec = gko::ReferenceExecutor::create();
} else if (argc == 2 && std::string(argv[1]) == "omp") {
    exec = gko::OmpExecutor::create();
```

```
} else if (argc == 2 && std::string(argv[1]) == "cuda" &&
           gko::CudaExecutor::get_num_devices() > 0) {
    exec = gko::CudaExecutor::create(0, gko::OmpExecutor::create(), true);
} else if (argc == 2 && std::string(argv[1]) == "hip" &&
           gko::HipExecutor::get_num_devices() > 0) {
    exec = gko::HipExecutor::create(0, gko::OmpExecutor::create(), true);
} else {
    std::cerr « "Usage: " « argv[0] « " [executor]" « std::endl;
    std::exit(-1);
}
```

Read data

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

Let's declare a logger which prints to std::cout instead of printing to a file. We log all events except for all linop factory and polymorphic object events. Events masks are group of events which are provided for convenience.

```
std::shared_ptr<gko::log::Stream<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 ResidualNormReduction 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::ResidualNormReduction<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>,0x562525b9cad0] with b
       LinOp[gko::matrix::Dense<double>,0x562525b9d670] and x
       LinOp[gko::matrix::Dense<double>,0x562525b9dca0]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c350]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c0f0]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[152]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2a30]
       with Bytes[152]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[152]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2c30]
       with Bytes[152]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[152]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e30]
       with Bytes[152]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[152]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3030]
       with Bytes[152]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3010]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3210]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3390]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3510]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[1]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3690]
       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>*>,0x7fffc24b0d30] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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>*>,0x7fffc24b0d30] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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>*>,0x7fffc24b0a80] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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>*>,0x7fffc24b0a80] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[2]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36d0]
       with Bytes[2]
```

```
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4360]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba43a0]
       with Bytes[8]
[LOG] »> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double>*>,0x7fffc24b0710] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double>*>,0x7fffc24b0710] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> copy started from Executor[gko::ReferenceExecutor,0x562525b99ec0] to
       Executor[gko::ReferenceExecutor,0x562525b99ec0] from Location[0x562525ba2a30] to
       Location[0x562525ba2c30] with Bytes[152]
[LOG] »> copy completed from Executor[gko::ReferenceExecutor,0x562525b99ec0] to
       Executor[gko::ReferenceExecutor,0x562525b99ec0] from Location[0x562525ba2a30] to
       Location[0x562525ba2c30] 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>*>,0x7fffc24b0a80] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> Operation[gko::matrix::dense::compute_dot_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double> const*, gko::matrix::Dense<double>*>,0x7fffc24b0a80] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> iteration 0 completed with solver LinOp[gko::solver::Cg<double>,0x562525b9cad0] with residual
       LinOp[gko::matrix::Dense<double>,0x562525b9e470], solution
       LinOp[gko::matrix::Dense<double>,0x562525b9dca0] and residual_norm LinOp[gko::LinOp const*,0]
[LOG] »> check started for stop::Criterion[gko::stop::ResidualNormReduction<double>,0x562525ba42a0] 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>*>,0x7fffc24b0800] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double>*>,0x7fffc24b0800] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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*&>,0x7fffc24b0a00] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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*&>,0x7fffc24b0a00] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> check completed for stop::Criterion[gko::stop::ResidualNormReduction<double>,0x562525ba42a0] 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,0x562525b99ec0] with Bytes[152]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4790]
       with Bytes[152]
.
.
.
.
.
.
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4830]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4830]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4790]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4790]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36d0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36d0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba43a0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba43a0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4360]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba4360]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3690]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3690]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3390]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3390]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3510]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3510]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3210]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3210]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3010]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3010]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3030]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba3030]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e30]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e30]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2c30]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2c30]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2a30]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2a30]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c0f0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c0f0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c350]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9c350]
[LOG] »> apply completed on A LinOp[gko::solver::Cg<double>,0x562525b9cad0] with b
```

```
       LinOp[gko::matrix::Dense<double>,0x562525b9d670] and x
       LinOp[gko::matrix::Dense<double>,0x562525b9dca0]
Last memory copied was of size 98 FROM executor 0x562525b99ec0 pointer 562525b9de80 TO executor
       0x562525b99ec0 pointer 562525ba5170
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,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba5720]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e10]
       with Bytes[8]
[LOG] »> allocation started on Executor[gko::ReferenceExecutor,0x562525b99ec0] with Bytes[8]
[LOG] »> allocation completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36b0]
       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>*>,0x7fffc24b0d10] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[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>*>,0x7fffc24b0d10] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double>*>,0x7fffc24b0d60] started on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
[LOG] »> Operation[gko::matrix::dense::compute_norm2_operation<gko::matrix::Dense<double> const*,
       gko::matrix::Dense<double>*>,0x7fffc24b0d60] completed on
       Executor[gko::ReferenceExecutor,0x562525b99ec0]
Residual norm sqrt(r^T r):
%%MatrixMarket matrix array real general
1 1
2.10788e-15
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36b0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba36b0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e10]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba2e10]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba5720]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525ba5720]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9de80]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9de80]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9dde0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9dde0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9d1a0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9d1a0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9d3c0]
```

```
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9d3c0]
[LOG] »> free started on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9dfb0]
[LOG] »> free completed on Executor[gko::ReferenceExecutor,0x562525b99ec0] at Location[0x562525b9dfb0]
```

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

```
    auto A = share(gko::read<mtx>(std::ifstream("data/A.mtx"), exec));
    auto b = gko::read<vec>(std::ifstream("data/b.mtx"), exec);
    auto x = gko::read<vec>(std::ifstream("data/x0.mtx"), exec);
    std::shared_ptr<gko::log::Stream<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::ResidualNormReduction<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 29

The three-pt-stencil-solver program

The 3-point stencil example..

This example depends on simple-solver, poisson-solver.

Introduction

This example solves a 1D Poisson equation:

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

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

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

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

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

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

The intention of the example is to show how Ginkgo can be integrated into existing software - the `generate_stencil_matrix`, `generate_rhs`, `print_solution`, `compute_error` and `main` function do not reference Ginkgo at all (i.e. they could have been there before the application developer decided to use Ginkgo, and the only part where Ginkgo is introduced is inside the `solve_system` function.

About the example

The commented program

```
/ ****************************<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_idxs,
                             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_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, 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);
         }},
        {"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 SpMVs to run (in this case `exec`). When creating array views, we have to specify the executor where the data is (in this case `app_exec`).

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

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

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

RHS: similar to matrix

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

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

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

Generate solver

```
auto solver_gen =
    cg::build()
        .with_criteria(gko::stop::Iteration::build()
                           .with_max_iters(gko::size_type(dp))
                           .on(exec),
                       gko::stop::ResidualNormReduction<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;
    if (argc < 2) {
        std::cerr « "Usage: " « argv[0] « " DISCRETIZATION_POINTS [executor]"
                 « std::endl;
        std::exit(-1);
    }
    const IndexType discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
```

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_idxs(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_idxs.data(), values.data());
```

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

```
    generate_rhs(discretization_points, f, u0, u1, rhs.data());
    solve_system(executor_string, discretization_points, row_ptrs.data(),
                 col_idxs.data(), values.data(), rhs.data(), u.data(),
                 reduction_factor);
    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:

```
0
0.00010798
0.000863838
0.00291545
0.0069107
0.0134975
0.0233236
0.037037
0.0552856
0.0787172
0.10798
0.143721
0.186589
0.237231
0.296296
0.364431
0.442285
0.530504
0.629738
0.740633
0.863838
1
The average relative error is 1.87318e-15
```

Comments about programming and debugging

The plain program

```
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OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
*****************************<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:

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>
template <typename ValueType, typename IndexType>
void generate_stencil_matrix(IndexType discretization_points,
                             IndexType *row_ptrs, IndexType *col_idxs,
                             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_idxs[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_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;
    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);
             }},
            {"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::ResidualNormReduction<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;
    if (argc < 2) {
        std::cerr << "Usage: " << argv[0] << " DISCRETIZATION_POINTS [executor]"
                  << std::endl;
        std::exit(-1);
    }
    const IndexType discretization_points =
        argc >= 2 ? std::atoi(argv[1]) : 100;
    const auto executor_string = argc >= 3 ? argv[2] : "reference";
    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);
    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;
}
```

Chapter 30

Module Documentation

30.1 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.

30.1.1 Detailed Description

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

30.2 Executors

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

Modules

- CUDA Executor

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

Macros

- #define GKO_REGISTER_OPERATION(_name, _kernel)

  Binds a set of device-specific kernels to an Operation.

30.2.1 Detailed Description

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

Below, we provide a brief introduction to executors in Ginkgo, how they have been implemented, how to best make use of them and how to add new executors.

30.2.2 Executors in Ginkgo.

The first step in using the Ginkgo library consists of creating an executor. Executors are used to specify the location for the data of linear algebra objects, and to determine where the operations will be executed. Ginkgo currently supports three different executor types:

- OpenMP Executor specifies that the data should be stored and the associated operations executed on an OpenMP-supporting device (e.g. host CPU);
- CUDA Executor specifies that the data should be stored and the operations executed on the NVIDIA GPU accelerator;
- HIP Executor uses the HIP library to compile code for either NVIDIA or AMD GPU accelerator;
- Reference Executor executes a non-optimized reference implementation, which can be used to debug the library.

30.2.3 Macro Definition Documentation

30.2.3.1 GKO_REGISTER_OPERATION

```
#define GKO_REGISTER_OPERATION(
              _name,
              _kernel )
```

Binds a set of device-specific kernels to an Operation.

It also defines a helper function which creates the associated operation. Any input arguments passed to the helper function are forwarded to the kernel when the operation is executed.

The kernels used to bind the operation are searched in `kernels::DEV_TYPE` namespace, where `DEV_TYPE` is replaced by `omp`, `cuda`, `hip` and `reference`.

Parameters

_name	operation name
_kernel	kernel which will be bound to the operation

30.2.3.2 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 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 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
    ref->run(op);  // run reference kernel
}
```

30.3 Factorizations

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

Namespaces

- gko::factorization

  The Factorization namespace.

Classes

- class gko::factorization::Ilu< ValueType, IndexType >

  Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.
- class gko::factorization::ParIct< ValueType, IndexType >

  ParICT is an incomplete threshold-based Cholesky factorization which is computed in parallel.
- class gko::factorization::ParIlu< ValueType, IndexType >

  ParILU is an incomplete LU factorization which is computed in parallel.
- class gko::factorization::ParIlut< ValueType, IndexType >

  ParILUT is an incomplete threshold-based LU factorization which is computed in parallel.

30.3.1 Detailed Description

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

30.4 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.

30.4.1 Detailed Description

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

30.5 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.

30.5.1 Detailed Description

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

30.6 Linear Operators

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

Modules

- Factorizations

  A module dedicated to the implementation and usage of the Factorizations in Ginkgo.
- SpMV employing different Matrix formats

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

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

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

Classes

- class gko::Combination< ValueType >

  The Combination class can be used to construct a linear combination of multiple linear operators `c1 * op1 + c2 * op2 + ...`
- class gko::Composition< ValueType >

  The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator `op1 * op2 * ...`
- class gko::LinOpFactory

  A LinOpFactory represents a higher order mapping which transforms one linear operator into another.
- class gko::ReadableFromMatrixData< ValueType, IndexType >

  A LinOp implementing this interface can read its data from a matrix_data structure.
- class gko::WritableToMatrixData< ValueType, IndexType >

  A LinOp implementing this interface can write its data to a matrix_data structure.
- class gko::Preconditionable

  A LinOp implementing this interface can be preconditioned.
- class gko::DiagonalExtractable< ValueType >

  The diagonal of a LinOp implementing this interface can be extracted.
- 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::Ilu< ValueType, IndexType >

  Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.
- class gko::factorization::ParIct< ValueType, IndexType >

  ParICT is an incomplete threshold-based Cholesky factorization which is computed in parallel.
- class gko::factorization::ParIlu< ValueType, IndexType >

  ParILU is an incomplete LU factorization which is computed in parallel.
- class gko::factorization::ParIlut< ValueType, IndexType >

  ParILUT 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::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::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::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 L x = b, when L is a lower triangular matrix.

- class gko::solver::UpperTrs< ValueType, IndexType >

  UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

Macros

- #define GKO_CREATE_FACTORY_PARAMETERS(_parameters_name, _factory_name)

  This Macro will generate a new type containing the parameters for the factory `_factory_name`.
- #define GKO_ENABLE_LIN_OP_FACTORY(_lin_op, _parameters_name, _factory_name)

  This macro will generate a default implementation of a LinOpFactory for the LinOp subclass it is defined in.
- #define GKO_ENABLE_BUILD_METHOD(_factory_name)

  Defines a build method for the factory, simplifying its construction by removing the repetitive typing of factory's name.
- #define GKO_FACTORY_PARAMETER(_name, ...)

  Creates a factory parameter in the factory parameters structure.
- #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.

30.6.1 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.

30.6.2 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.

30.6.3 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

30.6.4 Macro Definition Documentation

30.6.4.1 GKO_CREATE_FACTORY_PARAMETERS

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

Value:

```
public:                                                                 \
    class _factory_name;                                                \
    struct _parameters_name##_type                                      \
        : ::gko::enable_parameters_type<_parameters_name##_type,        \
                                        _factory_name>
```

This Macro will generate a new type containing the parameters for the factory `_factory_name`.

For more details, see GKO_ENABLE_LIN_OP_FACTORY(). It is required to use this macro **before** calling the macro GKO_ENABLE_LIN_OP_FACTORY(). It is also required to use the same names for all parameters between both macros.

Parameters

_parameters_name	name of the parameters member in the class
_factory_name	name of the generated factory type

30.6.4.2 GKO_ENABLE_BUILD_METHOD

```
#define GKO_ENABLE_BUILD_METHOD(
                _factory_name )
```

Value:

```
static auto build()->decltype(_factory_name::create())                  \
    {                                                                       \
        return _factory_name::create();                                     \
    }                                                                       \
    static_assert(true,                                                     \
                  "This assert is used to counter the false positive extra " \
                  "semi-colon warnings")
```

Defines a build method for the factory, simplifying its construction by removing the repetitive typing of factory's name.

Parameters

_factory_name	the factory for which to define the method

30.6.4.3 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

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

30.6.4.4 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

_name	name of the parameter
VA_ARGS	default value of the parameter

See also

GKO_ENABLE_LIN_OP_FACTORY for more details, and usage example

30.6.4.5 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

_name	name of the parameter
_default	default value of the parameter

See also

GKO_ENABLE_LIN_OP_FACTORY for more details, and usage example

30.6.4.6 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

_name	name of the parameter
_default	default value of the parameter

See also

GKO_ENABLE_LIN_OP_FACTORY for more details, and usage example

30.6.5 Typedef Documentation

30.6.5.1 EnableDefaultLinOpFactory

```
template<typename ConcreteFactory , typename ConcreteLinOp , typename ParametersType , typename
PolymorphicBase = LinOpFactory>
using gko::EnableDefaultLinOpFactory = typedef EnableDefaultFactory<ConcreteFactory, Concrete↩
LinOp, ParametersType, PolymorphicBase>
```

This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of LinOpFactory.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parmeter]
ConcreteLinOp	the concrete LinOp type which this factory produces, needs to have a constructor which takes a const ConcreteFactory $*$, and an std::shared_ptr<const LinOp> as parameters.
ParametersType	a subclass of enable_parameters_type template which defines all of the parameters of the factory
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of LinOpFactory

30.7 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.

30.7.1 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.

30.8 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 reordering 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.

30.8.1 Detailed Description

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

30.8.2 Function Documentation

30.8.2.1 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

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

Parameters

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

```
655 {
656     using dense = matrix::Dense<typename Matrix::value_type>;
657     size_type num_rows = vals.size();
658     size_type num_cols = num_rows > 0 ? begin(vals)->size() : 1;
659     auto tmp =
660         dense::create(exec->get_master(), dim<2>{num_rows, num_cols}, stride);
661     size_type ridx = 0;
662     for (const auto &row : vals) {
663         size_type cidx = 0;
664         for (const auto &elem : row) {
665             tmp->at(ridx, cidx) = elem;
666             ++cidx;
667         }
668         ++ridx;
669     }
670     auto mtx = Matrix::create(exec, std::forward<TArgs>(create_args)...);
671     tmp->move_to(mtx.get());
672     return mtx;
673 }
```

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

30.8.2.2 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

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

Parameters

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

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

30.8.2.3 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

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

Parameters

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

30.8.2.4 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

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

Parameters

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

30.9 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).

30.9.1 Detailed Description

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

30.10 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::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.

30.10.1 Detailed Description

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

30.11 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.

30.11.1 Detailed Description

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

30.12 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::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::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 L x = b, when L is a lower triangular matrix.
- class gko::solver::UpperTrs< ValueType, IndexType >

  UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

30.12.1 Detailed Description

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

30.13 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::ResidualNorm< ValueType >

  The ResidualNorm class provides a framework for stopping criteria related to the residual norm.
- 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 amout of time has passed.

Functions

- template<typename FactoryContainer >
  std::shared_ptr< const CriterionFactory > gko::stop::combine (FactoryContainer &&factories)

  Combines multiple criterion factories into a single combined criterion factory.

30.13.1 Detailed Description

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

30.13.2 Function Documentation

30.13.2.1 combine()

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

Combines multiple criterion factories into a single combined criterion factory.

This function treats a singleton container as a special case and avoids creating an additional object and just returns the input factory.

Template Parameters

FactoryContainer	a random access container type

Parameters

factories	a list of factories to combined

Returns

a combined criterion factory if the input contains multiple factories or the input factory if the input contains only one factory

```
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 31

Namespace Documentation

31.1 gko Namespace Reference

The Ginkgo namespace.

Namespaces

- accessor

  The accessor namespace.
- factorization

  The Factorization namespace.
- log

  The logger namespace .
- matrix

  The matrix namespace.
- name_demangling

  The name demangling namespace.
- preconditioner

  The Preconditioner namespace.
- solver

  The ginkgo Solve namespace.
- stop

  The Stopping criterion namespace.
- syn

  The Synthesizer namespace.
- xstd

  The namespace for functionalities after C++14 standard.

Classes

- class AbstractFactory

  The AbstractFactory is a generic interface template that enables easy implementation of the abstract factory design pattern.
- class AllocationError

  AllocationError is thrown if a memory allocation fails.
- class Array

  An Array is a container which encapsulates fixed-sized arrays, stored on the Executor tied to the Array.
- class BadDimension

  BadDimension is thrown if an operation is being applied to a LinOp with bad dimensions.
- class Combination

  The Combination class can be used to construct a linear combination of multiple linear operators `c1 * op1 + c2 * op2 + ...`
- class Composition

  The Composition class can be used to compose linear operators `op1, op2, ..., opn` *and obtain the operator* `op1 * op2 * ...`
- class ConvertibleTo

  ConvertibleTo interface is used to mark that the implementer can be converted to the object of ResultType.
- class copy_back_deleter

  A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.
- 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 CusparseError

  CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.
- struct default_converter

  Used to convert objects of type `S` *to objects of type* `R` *using static_cast.*
- 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.
- struct enable_parameters_type

  The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.
- class EnableAbstractPolymorphicObject

  This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new abstract object.
- class EnableCreateMethod

  This mixin implements a static `create()` *method on* `ConcreteType` *that dynamically allocates the memory, uses the passed-in arguments to construct the object, and returns an std::unique_ptr to such an object.*
- class EnableDefaultFactory

  This mixin provides a default implementation of a concrete factory.
- class EnableLinOp

The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.

- class EnablePolymorphicAssignment

  This mixin is used to enable a default PolymorphicObject::copy_from() implementation for objects that have implemented conversions between them.
- class EnablePolymorphicObject

  This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new concrete polymorphic object.
- class Error

  The Error class is used to report exceptional behaviour in library functions.
- class Executor

  The first step in using the Ginkgo library consists of creating an executor.
- class executor_deleter

  This is a deleter that uses an executor's `free` method to deallocate the data.
- class 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 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.
- 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 temporary_clone

  A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.
- class Transposable

  Linear operators which support transposition should implement the Transposable interface.
- 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 remove_complex = typename detail::remove_complex_impl< T >::type

  Obtains a real counterpart of a std::complex type, and leaves the type unchanged if it is not a complex type.
- template<typename T >
  using is_complex_s = detail::is_complex_impl< T >

  Allows to check if T is a complex value during compile time by accessing the `value` attribute of this struct.
- template<typename T >
  using 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 reduce_precision< T > round_down (T val)

  Reduces the precision of the input parameter.
- template<typename T >
  constexpr increase_precision< T > round_up (T val)

  Increases the precision of the input parameter.
- constexpr int64 ceildiv (int64 num, int64 den)

  Performs integer division with rounding up.
- template<typename T >
  constexpr T zero ()

  Returns the additive identity for T.
- template<typename T >
  constexpr T zero (const T &)

  Returns the additive identity for T.
- template<typename T >
  constexpr T one ()

  Returns the multiplicative identity for T.
- template<typename T >
  constexpr T one (const T &)

  Returns the multiplicative identity for T.
- template<typename T >
  constexpr T abs (const T &x)

  Returns the absolute value of the object.
- template<typename T >
  constexpr T max (const T &x, const T &y)

  Returns the larger of the arguments.
- template<typename T >
  constexpr T min (const T &x, const T &y)

  Returns the smaller of the arguments.
- template<typename T >
  constexpr 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 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)
- 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.
- template<typename T >
  temporary_clone< T > make_temporary_clone (std::shared_ptr< const Executor > exec, T *ptr)

  Creates a temporary_clone.
- std::ostream & operator<< (std::ostream &os, const version &ver)

  Prints version information to a stream.
- std::ostream & operator<< (std::ostream &os, const version_info &ver_info)

  Prints library version information in human-readable format to a stream.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (size_type stride, std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (std::initializer_list< typename Matrix::value_type > vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a column-vector.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (size_type stride, std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.
- template<typename Matrix , typename... TArgs>
  std::unique_ptr< Matrix > initialize (std::initializer_list< std::initializer_list< typename Matrix::value_type >> vals, std::shared_ptr< const Executor > exec, TArgs &&... create_args)

  Creates and initializes a matrix.
- bool operator== (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are equivalent.
- bool operator!= (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are different.

Variables

- constexpr size_type byte_size = CHAR_BIT

  Number of bits in a byte.

31.1.1 Detailed Description

The Ginkgo namespace.

31.1.2 Typedef Documentation

31.1.2.1 is_complex_s

```
template<typename T >
using gko::is_complex_s = typedef detail::is_complex_impl<T>
```

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

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

Template Parameters

T	type to check

31.1.3 Enumeration Type Documentation

31.1.3.1 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 };
```

31.1.4 Function Documentation

31.1.4.1 abs()

```
template<typename T >
constexpr T gko::abs (
            const T & x )  [inline], [constexpr]
```

Returns the absolute value of the object.

Template Parameters

T	the type of the object

Parameters

x	the object

Returns

x >= zero<T>() ? x : -x;

```
609 {
610     return x >= zero<T>() ? x : -x;
611 }
```

Referenced by is_finite().

31.1.4.2 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

T	requested result type
U	static type of the passed object

Parameters

obj	the object which should be converted

Returns

If successful, returns a pointer to the subtype, otherwise throws NotSupported.

```
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 }
```

31.1.4.3 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

T	requested result type
U	static type of the passed object

Parameters

obj	the shared_ptr 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.

31.1.4.4 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

T	requested result type
U	static type of the passed object

Parameters

obj	the shared_ptr 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.

31.1.4.5 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

T	requested result type
U	static type of the passed object

Parameters

obj	the unique_ptr to the object which should be converted. If successful, it will be reset to a nullptr.

Returns

If successful, returns a unique_ptr to the subtype, otherwise throws NotSupported.

31.1.4.6 as() [5/5]

```
template<typename T , typename U >
std::decay<T>::type* gko::as (
            U * obj )  [inline]
```

Performs polymorphic type conversion.

Template Parameters

T	requested result type
U	static type of the passed object

Parameters

obj	the object which should be converted

Returns

If successful, returns a pointer to the subtype, otherwise throws NotSupported.

31.1.4.7 ceildiv()

```
constexpr int64 gko::ceildiv (
            int64 num,
            int64 den )  [inline], [constexpr]
```

Performs integer division with rounding up.

Parameters

num	numerator
den	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().

31.1.4.8 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

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

The difference between this function and directly calling LinOp::clone() is that this one preserves the static type of the object.

Referenced by gko::temporary_clone< T >::temporary_clone().

31.1.4.9 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

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

exec	the executor where the cloned object should be stored
p	a pointer to the object

Note

The difference between this function and directly calling LinOp::clone() is that this one preserves the static type of the object.

31.1.4.10 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

x	the number to conjugate

Returns

conjugate of the object (by default, the object itself)

Referenced by squared_norm().

31.1.4.11 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

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a unique pointer (with dynamically bound deleter) to the converted object

Note

This is a version of the function which adds the const qualifier to the result if the input had the same qualifier.

```
490 {
491     return detail::copy_and_convert_to_impl<const R>(std::move(exec), obj);
492 }
```

31.1.4.12 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

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a shared pointer to the converted object

Note

This is a version of the function which adds the const qualifier to the result if the input had the same qualifier.

31.1.4.13 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

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a shared pointer to the converted object

31.1.4.14 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

R	the type to which the object should be converted
T	the type of the input object

Parameters

exec	the executor where the result should be placed
obj	the object that should be converted

Returns

a unique pointer (with dynamically bound deleter) to the converted object

31.1.4.15 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

T	a numeric type supporting bit shift and comparison

Parameters

n	a number
hint	a lower bound for the position o the significant bit

Returns

maximum of `hint` and the significant bit position of `n`

31.1.4.16 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

T	a numeric type supporting multiplication and comparison

Parameters

base	the base of the power to be returned
limit	the lower limit on the size of the power returned
hint	a lower bound on the result, has to be a power of base

Returns

the smallest power of `base` not smaller than `limit`

31.1.4.17 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

OwningPointer	type of pointer with ownership to the object (has to be a smart pointer)

Parameters

p	a pointer to the object

Note

The original pointer `p` becomes invalid after this call.

31.1.4.18 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

T	type of the object

Parameters

x	the object

Returns

imaginary part of the object (by default, zero<T>())

31.1.4.19 is_complex()

```
template<typename T >
constexpr bool gko::is_complex ( )  [inline], [constexpr]
```

Checks if T is a complex type.

Template Parameters

T	type to check

Returns

`true` if T is a complex type, `false` otherwise

31.1.4.20 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

T	type of the value to check

Parameters

value	value to check

Returns

`true` if the value is finite, meaning it are neither +/- infinity nor NaN.

References abs().

Referenced by is_finite().

31.1.4.21 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

T	complex type of the value to check

Parameters

value	complex value to check

Returns

`true` if both components of the given value are finite, meaning they are neither +/- infinity nor NaN.

References is_finite().

31.1.4.22 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

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

This is the overload for owning (smart) pointers, that behaves the same as calling .get() on the smart pointer.

Referenced by gko::log::EnableLogging< Executor >::remove_logger().

31.1.4.23 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

Pointer	type of pointer to the object (plain or smart pointer)

Parameters

p	a pointer to the object

Note

This is the overload for non-owning (plain) pointers, that just returns p.

31.1.4.24 make_temporary_clone()

```
template<typename T >
temporary_clone<T> gko::make_temporary_clone (
            std::shared_ptr< const Executor > exec,
            T * ptr )
```

Creates a temporary_clone.

This is a helper function which avoids the need to explicitly specify the type of the object, as would be the case if using the constructor of temporary_clone.

Parameters

exec	the executor where the clone will be created
ptr	a pointer to the object of which the clone will be created

Referenced by gko::matrix::Dense< ValueType >::add_scaled(), gko::matrix::Coo< ValueType, IndexType >::apply2(), gko::matrix::Dense< ValueType >::compute_dot(), gko::matrix::Dense< ValueType >::compute_norm2(), and gko::matrix::Dense< ValueType >::scale().

31.1.4.25 max()

```
template<typename T >
constexpr T gko::max (
            const T & x,
            const T & y )  [inline], [constexpr]
```

Returns the larger of the arguments.

Template Parameters

T	type of the arguments

Parameters

x	first argument
y	second argument

Returns

x >= y ? x : y

31.1.4.26 min()

```
template<typename T >
constexpr T gko::min (
            const T & x,
            const T & y )  [inline], [constexpr]
```

Returns the smaller of the arguments.

Template Parameters

T	type of the arguments

Parameters

x	first argument
y	second argument

Returns

x <= y ? x : y

Referenced by gko::matrix::Csr< ValueType, IndexType >::load_balance::clac_size().

31.1.4.27 one() [1/2]

```
template<typename T >
constexpr T gko::one ( )  [inline], [constexpr]
```

Returns the multiplicative identity for T.

Returns

the multiplicative identity for T

31.1.4.28 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)`.

31.1.4.29 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

Dimensionality	number of dimensions of the dim objects
DimensionType	datatype used to represent each dimension

Parameters

x	first object
y	second object

Returns

`!(x == y)`

```
221 {
222     return !(x == y);
223 }
```

31.1.4.30 operator"!=() [2/3]

```
bool gko::operator!= (
            const stopping_status & x,
            const stopping_status & y )  [inline], [noexcept]
```

Checks if two stopping statuses are different.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if `!(x == y)`

```
179 {
180     return x.data_ != y.data_;
181 }
```

31.1.4.31 operator"!=() [3/3]

```
constexpr bool gko::operator!= (
            precision_reduction x,
            precision_reduction y )  [constexpr], [noexcept]
```

Checks if two precision_reduction encodings are different.

Parameters

x	an encoding
y	an encoding

Returns

true if and only if x and y are different encodings.

```
374 {
375     using st = precision_reduction::storage_type;
376     return static_cast<st>(x) != static_cast<st>(y);
377 }
```

31.1.4.32 operator<<() [1/2]

```
std::ostream& gko::operator<< (
            std::ostream & os,
            const version & ver )  [inline]
```

Prints version information to a stream.

Parameters

os	output stream
ver	version structure

Returns

os

```
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.

31.1.4.33 operator<<() [2/2]

```
std::ostream& gko::operator<< (
            std::ostream & os,
            const version_info & ver_info )
```

Prints library version information in human-readable format to a stream.

Parameters

os	output stream
ver_info	version information

Returns

os

31.1.4.34 operator==() [1/2]

```
bool gko::operator== (
            const stopping_status & x,
            const stopping_status & y )  [inline], [noexcept]
```

Checks if two stopping statuses are equivalent.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if both x and y have the same mask and converged and finalized state

31.1.4.35 operator==() [2/2]

```
constexpr bool gko::operator== (
            precision_reduction x,
            precision_reduction y )  [constexpr], [noexcept]
```

Checks if two precision_reduction encodings are equal.

Parameters

x	an encoding
y	an encoding

Returns

true if and only if x and y are the same encodings

31.1.4.36 read()

```
template<typename MatrixType , typename StreamType , typename...  MatrixArgs>
std::unique_ptr<MatrixType> gko::read (
```

```
            StreamType && is,
            MatrixArgs &&... args )  [inline]
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

MatrixType	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
StreamType	type of stream used to write the data to
MatrixArgs	additional argument types passed to MatrixType constructor

Parameters

is	input stream from which to read the data
args	additional arguments passed to MatrixType constructor

Returns

A MatrixType LinOp filled with data from filename

References read_raw().

31.1.4.37 read_raw()

```
template<typename ValueType = default_precision, typename IndexType = int32>
matrix_data<ValueType, IndexType> gko::read_raw (
            std::istream & is )
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

ValueType	type of matrix values
IndexType	type of matrix indexes

Parameters

is	input stream from which to read the data

Returns

A matrix_data structure containing the matrix. The nonzero elements are sorted in lexicographic order of their (row, colum) indexes.

Note

This is an advanced routine that will return the raw matrix data structure. Consider using gko::read instead.

Referenced by read().

31.1.4.38 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

T	type of the object

Parameters

x	the object

Returns

real part of the object (by default, the object itself)

Referenced by squared_norm().

31.1.4.39 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

T	the original precision

Parameters

val	the value to round down

Returns

the rounded down value

31.1.4.40 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

T	the original precision

Parameters

val	the value to round up

Returns

the rounded up value

31.1.4.41 share()

```
template<typename OwningPointer >
detail::shared_type<OwningPointer> gko::share (
            OwningPointer && p )  [inline]
```

Marks the object pointed to by p as shared.

Effectively converts a pointer with ownership to std::shared_ptr.

Template Parameters

OwningPointer	type of pointer with ownership to the object (has to be a smart pointer)

Parameters

p	a pointer to the object

Note

The original pointer p becomes invalid after this call.

Referenced by gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose(), and gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::transpose().

31.1.4.42 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

T	type of the object.

Returns

The squared norm of the object.

References conj(), and real().

31.1.4.43 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

DimensionType	datatype used to represent each dimension

Parameters

dimensions	original object

Returns

a dim<2> object with its dimensions swapped

Referenced by gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose(), and gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::transpose().

31.1.4.44 write()

```
template<typename MatrixType , typename StreamType >
void gko::write (
```

```
            StreamType && os,
            MatrixType * matrix,
            layout_type layout = layout_type::array )  [inline]
```

Reads a matrix stored in matrix market format from an input stream.

Template Parameters

MatrixType	a ReadableFromMatrixData LinOp type used to store the matrix once it's been read from disk.
StreamType	type of stream used to write the data to

Parameters

os	output stream where the data is to be written
matrix	the matrix to write
layout	the layout used in the output

References write_raw().

31.1.4.45 write_raw()

```
template<typename ValueType , typename IndexType >
void gko::write_raw (
            std::ostream & os,
            const matrix_data< ValueType, IndexType > & data,
            layout_type layout = layout_type::array )
```

Writes a matrix_data structure to a stream in matrix market format.

Template Parameters

ValueType	type of matrix values
IndexType	type of matrix indexes

Parameters

os	output stream where the data is to be written
data	the matrix data to write
layout	the layout used in the output

Note

This is an advanced routine that writes the raw matrix data structure. If you are trying to write an existing matrix, consider using gko::write instead.

Referenced by write().

31.1.4.46 zero() [1/2]

```
template<typename T >
constexpr T gko::zero ( )  [inline], [constexpr]
```

Returns the additive identity for T.

Returns

additive identity for T

31.1.4.47 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)`.

31.2 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.

31.2.1 Detailed Description

The accessor namespace.

31.3 gko::factorization Namespace Reference

The Factorization namespace.

Classes

- class Ilu

  Represents an incomplete LU factorization – ILU(0) – of a sparse matrix.
- class ParIct

  ParICT is an incomplete threshold-based Cholesky factorization which is computed in parallel.
- class ParIlu

  ParILU is an incomplete LU factorization which is computed in parallel.
- class ParIlut

  ParILUT is an incomplete threshold-based LU factorization which is computed in parallel.

31.3.1 Detailed Description

The Factorization namespace.

31.4 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.

31.4.1 Detailed Description

The logger namespace .

The Logging namespace.

Logging

31.5 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).

31.5.1 Detailed Description

The matrix namespace.

31.6 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.

31.6.1 Detailed Description

The name demangling namespace.

31.6.2 Function Documentation

31.6.2.1 get_dynamic_type()

```
template<typename T >
std::string gko::name_demangling::get_dynamic_type (
            const T & t )
```

This function uses name demangling facilities to get the name of the dynamic type of the object passed in arguments.

Template Parameters

T	the type of the object to demangle

Parameters

t	the object we get the dynamic type of

```
101 {
102     return get_type_name(typeid(t));
103 }
```

31.6.2.2 get_static_type()

```
template<typename T >
std::string gko::name_demangling::get_static_type (
            const T &  )
```

This function uses name demangling facilities to get the name of the static type (`T`) of the object passed in arguments.

Template Parameters

T	the type of the object to demangle

Parameters

unused	

31.7 gko::preconditioner Namespace Reference

The Preconditioner namespace.

Classes

- struct block_interleaved_storage_scheme

  Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.
- class Ilu

  The Incomplete LU (ILU) preconditioner solves the equation $LUx = b$ for a given lower triangular matrix L, an upper triangular matrix U and the right hand side b (can contain multiple right hand sides).
- class Isai

  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.

31.7.1 Detailed Description

The Preconditioner namespace.

31.7.2 Enumeration Type Documentation

31.7.2.1 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 };

31.8 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 Cg

  CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class Cgs

  CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.
- class Fcg

  FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.
- class Gmres

  GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.
- class Ir

  Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.
- class LowerTrs

  LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.
- class UpperTrs

  UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

31.8.1 Detailed Description

The ginkgo Solve namespace.

31.9 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 EnableDefaultCriterionFactoryCriterionFactory::generate() method.
- 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 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 amout of time has passed.

Typedefs

- using CriterionFactory = AbstractFactory< Criterion, CriterionArgs >

  Declares an Abstract Factory specialized for Criterions.
- template<typename ConcreteFactory , typename ConcreteCriterion , typename ParametersType , typename PolymorphicBase = CriterionFactory>
  using EnableDefaultCriterionFactory = EnableDefaultFactory< ConcreteFactory, ConcreteCriterion, ParametersType, PolymorphicBase >

  This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of CriterionFactory.

Functions

- template<typename FactoryContainer >
  std::shared_ptr< const CriterionFactory > combine (FactoryContainer &&factories)

  Combines multiple criterion factories into a single combined criterion factory.

31.9.1 Detailed Description

The Stopping criterion namespace.

Stopping criteria

31.9.2 Typedef Documentation

31.9.2.1 EnableDefaultCriterionFactory

```
template<typename ConcreteFactory , typename ConcreteCriterion , typename ParametersType ,
typename PolymorphicBase = CriterionFactory>
using gko::stop::EnableDefaultCriterionFactory = typedef EnableDefaultFactory<ConcreteFactory,
ConcreteCriterion, ParametersType, PolymorphicBase>
```

This is an alias for the EnableDefaultFactory mixin, which correctly sets the template parameters to enable a subclass of CriterionFactory.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parmeter]
ConcreteCriterion	the concrete Criterion type which this factory produces, needs to have a constructor which takes a const ConcreteFactory $*$, and a const CriterionArgs $*$ as parameters.
ParametersType	a subclass of enable_parameters_type template which defines all of the parameters of the factory
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of CriterionFactory

31.10 gko::syn Namespace Reference

The Synthesizer namespace.

31.10.1 Detailed Description

The Synthesizer namespace.

31.11 gko::xstd Namespace Reference

The namespace for functionalities after C++14 standard.

31.11.1 Detailed Description

The namespace for functionalities after C++14 standard.

Chapter 32

Class Documentation

32.1 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>`

32.1.1 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 norm(residual) / 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

32.2 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.

32.2.1 Detailed Description

template<typename AbstractProductType, typename ComponentsType>
class gko::AbstractFactory< AbstractProductType, ComponentsType >

The AbstractFactory is a generic interface template that enables easy implementation of the abstract factory design pattern.

The interface provides the AbstractFactory::generate() method that can produce products of type `AbstractProductType` using an object of `ComponentsType` (which can be constructed on the fly from parameters to its constructors). The generate() method is not declared as virtual, as this allows subclasses to hide the method with a variant that preserves the compile-time type of the objects. Instead, implementers should override the generate_impl() method, which is declared virtual.

Implementers of concrete factories should consider using the EnableDefaultFactory mixin to obtain default implementations of utility methods of PolymorphicObject and AbstractFactory.

Template Parameters

AbstractProductType	the type of products the factory produces
ComponentsType	the type of components the factory needs to produce the product

32.2.2 Member Function Documentation

32.2.2.1 generate()

```
template<typename AbstractProductType, typename ComponentsType>
template<typename...  Args>
std::unique_ptr<AbstractProductType> gko::AbstractFactory< AbstractProductType, Components
Type >::generate (
            Args &&...  args ) const  [inline]
```

Creates a new product from the given components.

The method will create an ComponentsType object from the arguments of this method, and pass it to the generate_impl() function which will create a new AbstractProductType.

Template Parameters

Args	types of arguments passed to the constructor of ComponentsType

Parameters

args	arguments passed to the constructor of ComponentsType

Returns

an instance of AbstractProductType

```
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

32.3 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.

32.3.1 Detailed Description

AllocationError is thrown if a memory allocation fails.

32.3.2 Constructor & Destructor Documentation

32.3.2.1 AllocationError()

```
gko::AllocationError::AllocationError (
            const std::string & file,
            int line,
            const std::string & device,
            size_type bytes )  [inline]
```

Initializes an allocation error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
device	The device on which the error occurred
bytes	The size of the memory block whose allocation failed.

```
418         : Error(file, line,
419                 device + ": failed to allocate memory block of " +
420                     std::to_string(bytes) + "B")
421     {}
```

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.4 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.
- 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.

32.4.1 Detailed Description

template<typename ValueType>
class gko::Array< ValueType >

An Array is a container which encapsulates fixed-sized arrays, stored on the Executor tied to the Array.

The array stores and transfers its data as **raw** memory, which means that the constructors of its elements are not called when constructing, copying or moving the Array. Thus, the Array class is most suitable for storing POD types.

Template Parameters

ValueType	the type of elements stored in the array

32.4.2 Constructor & Destructor Documentation

32.4.2.1 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     {}
```

32.4.2.2 Array() [2/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec )  [inline], [noexcept]
```

Creates an empty Array tied to the specified Executor.

Parameters

exec	the Executor where the array data is allocated

32.4.2.3 Array() [3/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems )  [inline]
```

Creates an Array on the specified Executor.

Parameters

exec	the Executor where the array data will be allocated
num_elems	the amount of memory (expressed as the number of `value_type` elements) allocated on the Executor

32.4.2.4 Array() [4/11]

```
template<typename ValueType>
template<typename DeleterType >
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems,
            value_type * data,
            DeleterType deleter )  [inline]
```

Creates an Array from existing memory.

The memory will be managed by the array, and deallocated using the specified deleter (e.g. use std::default_delete for data allocated with new).

Template Parameters

DeleterType	type of the deleter

Parameters

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array
deleter	the deleter used to free the memory

See also

Array::view() to create an array that does not deallocate memory

Array(std::shared_ptr<cont Executor>, size_type, value_type*) to deallocate the memory using Executor::free() method

32.4.2.5 Array() [5/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            size_type num_elems,
            value_type * data )  [inline]
```

Creates an Array from existing memory.

The memory will be managed by the array, and deallocated using the Executor::free method.

Parameters

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array

32.4.2.6 Array() [6/11]

```
template<typename ValueType>
template<typename RandomAccessIterator >
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            RandomAccessIterator begin,
            RandomAccessIterator end )  [inline]
```

Creates an array on the specified Executor and initializes it with values.

Template Parameters

RandomAccessIterator	type of the iterators

Parameters

exec	the Executor where the array data will be allocated
begin	start of range of values
end	end of range of values

32.4.2.7 Array() [7/11]

```
template<typename ValueType>
template<typename T >
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            std::initializer_list< T > init_list )  [inline]
```

Creates an array on the specified Executor and initializes it with values.

Template Parameters

T	type of values used to initialize the array (T has to be implicitly convertible to value_type)

Parameters

exec	the Executor where the array data will be allocated

Parameters

init_list	list of values used to initialize the Array

32.4.2.8 Array() [8/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            const Array< ValueType > & other )  [inline]
```

Creates a copy of another array on a different executor.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

exec	the executor where the new array will be created
other	the Array to copy from

32.4.2.9 Array() [9/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            const Array< ValueType > & other )  [inline]
```

Creates a copy of another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

other	the Array to copy from

32.4.2.10 Array() [10/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            std::shared_ptr< const Executor > exec,
            Array< ValueType > && other )  [inline]
```

Moves another array to a different executor.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

exec	the executor where the new array will be moved
other	the Array to move

32.4.2.11 Array() [11/11]

```
template<typename ValueType>
gko::Array< ValueType >::Array (
            Array< ValueType > && other )  [inline]
```

Moves another array.

This does not invoke the constructors of the elements, instead they are copied as POD types.

Parameters

other	the Array to move

32.4.3 Member Function Documentation

32.4.3.1 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().

32.4.3.2 get_const_data()

```
template<typename ValueType>
const value_type* gko::Array< ValueType >::get_const_data ( ) const  [inline], [noexcept]
```

Returns a constant pointer to the block of memory used to store the elements of the Array.

Returns

a constant pointer to the block of memory used to store the elements of the Array

Referenced by gko::matrix::Dense< ValueType >::at(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_blocks(), gko::preconditioner::Jacobi< ValueType, IndexType >::get_conditioning(), gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Csr< ValueType, IndexType >::get_const_col_idxs(), gko::matrix::Permutation< IndexType >::get_const_permutation(), gko::matrix::Coo< ValueType, IndexType >::get_const_row_idxs(), 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().

32.4.3.3 get_data()

```
template<typename ValueType>
value_type* gko::Array< ValueType >::get_data ( )  [inline], [noexcept]
```

Returns a pointer to the block of memory used to store the elements of the Array.

Returns

a pointer to the block of memory used to store the elements of the Array

Referenced by gko::matrix::Dense< ValueType >::at(), gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_stored_elements_per_row(), gko::matrix::SparsityCsr< ValueType, IndexType >::get_col_idxs(), gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs(), gko::matrix::Ell< ValueType, IndexType >::get_col_idxs(), gko::matrix::Coo< ValueType, IndexType >::get_col_idxs(), gko::matrix::Csr< ValueType, IndexType >::get_col_idxs(), gko::matrix::Permutation< IndexType >::get_permutation(), gko::matrix::Coo< ValueType, IndexType >::get_row_idxs(), 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().

32.4.3.4 get_executor()

```
template<typename ValueType>
std::shared_ptr<const Executor> gko::Array< ValueType >::get_executor ( ) const  [inline],
[noexcept]
```

Returns the Executor associated with the array.

Returns

the Executor associated with the array

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config(), gko::Array< index_type >::operator=(), gko::matrix::Csr< ValueType, IndexType >::classical::process(), and gko::matrix::Csr< ValueType, IndexType >::load_balance::process().

32.4.3.5 get_num_elems()

```
template<typename ValueType>
size_type gko::Array< ValueType >::get_num_elems ( ) const  [inline], [noexcept]
```

Returns the number of elements in the Array.

Returns

the number of elements in the Array

Referenced by gko::matrix::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::matrix::Dense< ValueType >::get_num_stored_elements(), gko::preconditioner::Jacobi< ValueType, IndexType >::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().

32.4.3.6 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().

32.4.3.7 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

other	the Array to move data from

Returns

this

32.4.3.8 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

other	the Array to copy from

Returns

this

32.4.3.9 operator=() [3/3]

```
template<typename ValueType>
template<typename OtherValueType >
std::enable_if_t<!std::is_same<ValueType, OtherValueType>::value, Array>& gko::Array< Value↩
Type >::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

other	the Array to copy from

Template Parameters

OtherValueType	the value type of `other`

Returns

this

32.4.3.10 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

num_elems	the amount of memory (expressed as the number of `value_type` elements) allocated on the Executor

Referenced by gko::Array< index_type >::operator=().

32.4.3.11 set_executor()

```
template<typename ValueType>
void gko::Array< ValueType >::set_executor (
            std::shared_ptr< const Executor > exec )  [inline]
```

Changes the Executor of the Array, moving the allocated data to the new Executor.

Parameters

exec	the Executor where the data will be moved to

32.4.3.12 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

exec	executor where `data` is located
num_elems	number of elements in `data`
data	chunk of memory used to create the array

Returns

an Array constructed from `data`

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

The documentation for this class was generated from the following file:

- ginkgo/core/base/array.hpp

32.5 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.

32.5.1 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.

32.5.2 Member Function Documentation

32.5.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::automatic::compute_ell_num_stored_↩
elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::matrix::Hybrid< ValueType, IndexType >::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

32.6 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.

32.6.1 Detailed Description

BadDimension is thrown if an operation is being applied to a LinOp with bad dimensions.

32.6.2 Constructor & Destructor Documentation

32.6.2.1 BadDimension()

```
gko::BadDimension::BadDimension (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & op_name,
            size_type op_num_rows,
            size_type op_num_cols,
            const std::string & clarification )  [inline]
```

Initializes a bad dimension error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The function name where the error occurred
op_name	The name of the operator
op_num_rows	The row dimension of the operator
op_num_cols	The column dimension of the operator
clarification	An additional message further describing the error

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.7 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.

32.7.1 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 the unstable version of BiCGSTAB.

Template Parameters

ValueType	precision of matrix elements

32.7.2 Member Function Documentation

32.7.2.1 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.

```
100 { return true; }
```

32.7.2.2 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.

32.7.2.3 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

32.7.2.4 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)

32.7.2.5 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

other	the new stopping criterion factory

32.7.2.6 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

32.8 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.

32.8.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Bicgstab< ValueType >

BiCGSTAB or the Bi-Conjugate Gradient-Stabilized is a Krylov subspace solver.

Being a generic solver, it is capable of solving general matrices, including non-s.p.d matrices. Though, the memory and the computational requirement of the BiCGSTAB solver are higher than of its s.p.d solver counterpart, it has the capability to solve generic systems. It was developed by stabilizing the BiCG method.

Template Parameters

ValueType	precision of the elements of the system matrix.

32.8.2 Member Function Documentation

32.8.2.1 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; }
```

32.8.2.2 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.

32.8.2.3 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

32.8.2.4 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)

32.8.2.5 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

other	the new stopping criterion factory

32.8.2.6 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

32.9 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.

32.9.1 Detailed Description

template<typename IndexType>
struct gko::preconditioner::block_interleaved_storage_scheme< IndexType >

Defines the parameters of the interleaved block storage scheme used by block-Jacobi blocks.

Template Parameters

IndexType	type used for storing indices of the matrix

32.9.2 Member Function Documentation

32.9.2.1 compute_storage_space()

```
template<typename IndexType>
size_type gko::preconditioner::block_interleaved_storage_scheme< IndexType >::compute_storage↩
_space (
            size_type num_blocks ) const  [inline], [noexcept]
```

Computes the storage space required for the requested number of blocks.

Parameters

num_blocks	the total number of blocks that needs to be stored

Returns

the total memory (as the number of elements) that need to be allocated for the scheme

Note

To simplify using the method in situations where the number of blocks is not known, for a special input `size↩_type{} - 1` the method returns `0` to avoid overallocation of memory.

```
112     {
113         return (num_blocks + 1 == size_type{0})
114                    ? size_type{0}
115                    : ceildiv(num_blocks, this->get_group_size()) * group_offset;
116     }
```

32.9.2.2 get_block_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_block_offset
(
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the block with the given ID within its group.

Parameters

block↩_id	the ID of the block

Returns

the offset of the block with ID `block_id` within its group

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_global_block_offset().

32.9.2.3 get_global_block_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_global_↩
block_offset (
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the block with the given ID.

Parameters

block↩ _id	the ID of the block

Returns

the offset of the block with ID `block_id`

32.9.2.4 get_group_offset()

```
template<typename IndexType>
IndexType gko::preconditioner::block_interleaved_storage_scheme< IndexType >::get_group_offset
(
            IndexType block_id ) const  [inline], [noexcept]
```

Returns the offset of the group belonging to the block with the given ID.

Parameters

block↩ _id	the ID of the block

Returns

the offset of the group belonging to block with ID `block_id`

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_global_block_offset().

32.9.2.5 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().

32.9.2.6 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

32.9.3 Member Data Documentation

32.9.3.1 group_power

```
template<typename IndexType>
uint32 gko::preconditioner::block_interleaved_storage_scheme< IndexType >::group_power
```

Then base 2 power of the group.

I.e. the group contains `1 << group_power` elements.

Referenced by gko::preconditioner::block_interleaved_storage_scheme< index_type >::get_group_offset(), 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

32.10 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.

32.10.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Cg< ValueType >

CG or the conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

Though this method performs very well for symmetric positive definite matrices, it is in general not suitable for general matrices.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of CG are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

32.10.2 Member Function Documentation

32.10.2.1 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; }
```

32.10.2.2 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.

32.10.2.3 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

32.10.2.4 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)

32.10.2.5 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

other	the new stopping criterion factory

32.10.2.6 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

32.11 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.

32.11.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Cgs< ValueType >

CGS or the conjugate gradient square method is an iterative type Krylov subspace method which is suitable for general systems.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of CGS are merged into 3 separate steps.

Template Parameters

ValueType	precision of matrix elements

32.11.2 Member Function Documentation

32.11.2.1 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; }
```

32.11.2.2 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.

32.11.2.3 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

32.11.2.4 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)

32.11.2.5 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

other	the new stopping criterion factory

32.11.2.6 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

32.12 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.

32.12.1 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.

32.12.2 Member Function Documentation

32.12.2.1 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

nnz	the number of nonzeros

Returns

the size of srow

Implements gko::matrix::Csr< ValueType, IndexType >::strategy_type.

32.12.2.2 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.

32.12.2.3 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.13 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.

32.13.1 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.

32.13.2 Constructor & Destructor Documentation

32.13.2.1 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

32.13.3 Member Function Documentation

32.13.3.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::column_limit::compute_ell_num_stored_↩
elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp

32.14 gko::Combination< ValueType > Class Template Reference

The Combination class can be used to construct a linear combination of multiple linear operators `c1 * op1 + c2 * op2 + ...`

`#include <ginkgo/core/base/combination.hpp>`

Public Member Functions

- const std::vector< std::shared_ptr< const LinOp > > & get_coefficients () const noexcept
  Returns a list of coefficients of the combination.
- const std::vector< std::shared_ptr< const LinOp > > & get_operators () const noexcept
  Returns a list of operators of the combination.
- 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.

32.14.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Combination< ValueType >

The Combination class can be used to construct a linear combination of multiple linear operators `c1 * op1 + c2 * op2 + ...`

- ck * opk.

Template Parameters

ValueType	precision of input and result vectors

32.14.2 Member Function Documentation

32.14.2.1 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.

32.14.2.2 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     }
```

32.14.2.3 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

32.14.2.4 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

32.15 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>`

32.15.1 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

32.16 gko::Composition< ValueType > Class Template Reference

The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator `op1 * op2 * ...`

`#include <ginkgo/core/base/composition.hpp>`

Public Member Functions

- const std::vector< std::shared_ptr< const LinOp > > & get_operators () const noexcept
  Returns a list of operators of the composition.
- 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.

32.16.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Composition< ValueType >

The Composition class can be used to compose linear operators `op1, op2, ..., opn` and obtain the operator `op1 * op2 * ...`

- opn.

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}->apply` if `op_k` has square dimension
- zero if `op_k` is rectangular as an initial guess.

Template Parameters

ValueType	precision of input and result vectors

32.16.2 Member Function Documentation

32.16.2.1 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.

32.16.2.2 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     }
```

32.16.2.3 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

32.17 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.

32.17.1 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.

32.17.2 Member Function Documentation

32.17.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Convergence> gko::log::Convergence< ValueType >::create (
            std::shared_ptr< const Executor > exec,
            const mask_type & enabled_events = Logger::all_events_mask )  [inline], [static]
```

Creates a convergence logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.

Returns

an std::unique_ptr to the the constructed object

```
92     {
93         return std::unique_ptr<Convergence>(
94             new Convergence(exec, enabled_events));
95     }
```

32.17.2.2 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

32.17.2.3 get_residual()

```
template<typename ValueType = default_precision>
const LinOp* gko::log::Convergence< ValueType >::get_residual ( ) const  [inline], [noexcept]
```

Returns the residual.

Returns

the residual

32.17.2.4 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

32.18 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.

32.18.1 Detailed Description

template<typename ResultType>
class gko::ConvertibleTo< ResultType >

ConvertibleTo interface is used to mark that the implementer can be converted to the object of ResultType.

This interface is used to enable conversions between polymorphic objects. To mark that an object of type `U` can be converted to an object of type `V`, `U` should implement ConvertibleTo<V>. Then, the implementation of `PolymorphicObject::copy_from` automatically generated by `EnablePolymorphicObject` mixin will use RTTI to figure out that `U` implements the interface and convert it using the convert_to / move_to methods of the interface.

As an example, the following function:

```
 {c++}
void my_function(const U *u, V *v) {
    v->copy_from(u);
}
```

will convert object `u` to object `v` by checking that `u` can be dynamically casted to `ConvertibleTo\<V\>`, and calling ConvertibleTo<V>::convert_to(V*)` to do the actual conversion.

In case `u` is passed as a unique_ptr, call to `convert_to` will be replaced by a call to `move_to` and trigger move semantics.

Template Parameters

ResultType	the type to which the implementer can be converted to, has to be a subclass of PolymorphicObject

32.18.2 Member Function Documentation

32.18.2.1 convert_to()

```
template<typename ResultType>
virtual void gko::ConvertibleTo< ResultType >::convert_to (
            result_type * result ) const  [pure virtual]
```

Converts the implementer to an object of type result_type.

Parameters

result	the object used to store the result of the conversion

Implemented in gko::EnablePolymorphicAssignment< ConcreteType, ResultType >, gko::EnablePolymorphicAssignment< Isai< Isa
gko::EnablePolymorphicAssignment< SparsityCsr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Diagonal< V
gko::EnablePolymorphicAssignment< Dense< ValueType > >, gko::EnablePolymorphicAssignment< UpperTrs< ValueType, Index
gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Identity< ValueTy
gko::EnablePolymorphicAssignment< ConcreteLinOp >, gko::EnablePolymorphicAssignment< Composition< ValueType > >,
gko::EnablePolymorphicAssignment< Bicgstab< ValueType > >, gko::EnablePolymorphicAssignment< LowerTrs< ValueType, Inde
gko::EnablePolymorphicAssignment< Combination< ValueType > >, gko::EnablePolymorphicAssignment< Gmres< ValueType >
gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ir< ValueType > >,
gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Fcg< ValueType >
gko::EnablePolymorphicAssignment< ConcreteFactory >, gko::EnablePolymorphicAssignment< Cgs< ValueType > >,
gko::EnablePolymorphicAssignment< Ell< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ilu< LSolverType, US
gko::EnablePolymorphicAssignment< Permutation< IndexType > >, gko::EnablePolymorphicAssignment< Jacobi< ValueType, Ind
gko::EnablePolymorphicAssignment< Cg< ValueType > >, gko::EnablePolymorphicAssignment< Sellp< ValueType, IndexType >
gko::EnablePolymorphicAssignment< Bicg< ValueType > >, gko::EnablePolymorphicAssignment< Perturbation< ValueType > >,
and gko::preconditioner::Jacobi< ValueType, IndexType >.

32.18.2.2 move_to()

```
template<typename ResultType>
virtual void gko::ConvertibleTo< ResultType >::move_to (
            result_type * result )  [pure virtual]
```

Converts the implementer to an object of type result_type by moving data from this object.

This method is used when the implementer is a temporary object, and move semantics can be used.

Parameters

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implemented in gko::EnablePolymorphicAssignment< ConcreteType, ResultType >, gko::EnablePolymorphicAssignment< Isai< Isa
gko::EnablePolymorphicAssignment< SparsityCsr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Diagonal< V
gko::EnablePolymorphicAssignment< Dense< ValueType > >, gko::EnablePolymorphicAssignment< UpperTrs< ValueType, Index
gko::EnablePolymorphicAssignment< Hybrid< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Identity< ValueTy
gko::EnablePolymorphicAssignment< ConcreteLinOp >, gko::EnablePolymorphicAssignment< Composition< ValueType > >,
gko::EnablePolymorphicAssignment< Bicgstab< ValueType > >, gko::EnablePolymorphicAssignment< LowerTrs< ValueType, Inde
gko::EnablePolymorphicAssignment< Combination< ValueType > >, gko::EnablePolymorphicAssignment< Gmres< ValueType >
gko::EnablePolymorphicAssignment< Csr< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ir< ValueType > >,
gko::EnablePolymorphicAssignment< Coo< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Fcg< ValueType >
gko::EnablePolymorphicAssignment< ConcreteFactory >, gko::EnablePolymorphicAssignment< Cgs< ValueType > >,

gko::EnablePolymorphicAssignment< Ell< ValueType, IndexType > >, gko::EnablePolymorphicAssignment< Ilu< LSolverType, US
gko::EnablePolymorphicAssignment< Permutation< IndexType > >, gko::EnablePolymorphicAssignment< Jacobi< ValueType, Ind
gko::EnablePolymorphicAssignment< Cg< ValueType > >, 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

32.19 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.
- value_type * get_values () noexcept
  Returns the values of the matrix.
- const value_type * get_const_values () const noexcept
  Returns the values of the matrix.
- index_type * get_col_idxs () noexcept
  Returns the column indexes of the matrix.
- const index_type * get_const_col_idxs () const noexcept
  Returns the column indexes of the matrix.
- index_type * get_row_idxs () noexcept
  Returns the row indexes of the matrix.
- const index_type * get_const_row_idxs () const noexcept
- size_type get_num_stored_elements () const noexcept
  Returns the number of elements explicitly stored in the matrix.
- LinOp * apply2 (const LinOp *b, LinOp *x)
  Applies Coo matrix axpy to a vector (or a sequence of vectors).
- const LinOp * apply2 (const LinOp *b, LinOp *x) const
- LinOp * apply2 (const LinOp *alpha, const LinOp *b, LinOp *x)
  *Performs the operation x = alpha * Coo * b + x.*
- const LinOp * apply2 (const LinOp *alpha, const LinOp *b, LinOp *x) const
  *Performs the operation x = alpha * Coo * b + x.*

32.19.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Coo< ValueType, IndexType >

COO stores a matrix in the coordinate matrix format.

The nonzero elements are stored in an array row-wise (but not neccessarily sorted by column index within a row). Two extra arrays contain the row and column indexes of each nonzero element of the matrix.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.19.2 Member Function Documentation

32.19.2.1 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 = alpha ∗ Coo ∗ b + x.

Parameters

alpha	scaling of the result of Coo ∗ b
b	vector(s) on which the operator is applied
x	output vector(s)

Returns

this

```
228     {
229         this->validate_application_parameters(b, x);
230         GKO_ASSERT_EQUAL_DIMENSIONS(alpha, dim<2>(1, 1));
231         auto exec = this->get_executor();
232         this->apply2_impl(make_temporary_clone(exec, alpha).get(),
233                           make_temporary_clone(exec, b).get(),
234                           make_temporary_clone(exec, x).get());
235         return this;
236     }
```

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.19.2.2 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 = alpha ∗ Coo ∗ b + x.

Parameters

alpha	scaling of the result of Coo * b
b	vector(s) on which the operator is applied
x	output vector(s)

Returns

this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.19.2.3 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 = Coo * b + x

Parameters

b	the input vector(s) on which the operator is applied
x	the output vector(s) where the result is stored

Returns

this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.19.2.4 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().

32.19.2.5 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.19.2.6 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().

32.19.2.7 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().

32.19.2.8 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().

32.19.2.9 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().

32.19.2.10 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().

32.19.2.11 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().

32.19.2.12 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().

32.19.2.13 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Coo< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.19.2.14 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Coo< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/coo.hpp

32.20 gko::copy_back_deleter< T > Class Template Reference

A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.

`#include <ginkgo/core/base/utils.hpp>`

Public Member Functions

- copy_back_deleter (pointer original)

  Creates a new deleter object.
- void operator() (pointer ptr) const

  Deletes the object.

32.20.1 Detailed Description

template<typename T>
class gko::copy_back_deleter< T >

A copy_back_deleter is a type of deleter that copies the data to an internally referenced object before performing the deletion.

The deleter will use the `copy_from` method to perform the copy, and then delete the passed object using the `delete` keyword. This kind of deleter is useful when temporarily copying an object with the intent of copying it back once it goes out of scope.

There is also a specialization for constant objects that does not perform the copy, since a constant object couldn't have been changed.

Template Parameters

T	the type of object being deleted

32.20.2 Constructor & Destructor Documentation

32.20.2.1 copy_back_deleter()

```
template<typename T >
gko::copy_back_deleter< T >::copy_back_deleter (
            pointer original )  [inline]
```

Creates a new deleter object.

Parameters

original	the origin object where the data will be copied before deletion

32.20.3 Member Function Documentation

32.20.3.1 operator()()

```
template<typename T >
void gko::copy_back_deleter< T >::operator() (
            pointer ptr ) const  [inline]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp

32.21 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.

32.21.1 Detailed Description

template<typename T>
struct gko::cpx_real_type< T >

Access the underlying real type of a complex number.

Template Parameters

T	the type being checked.

32.21.2 Member Typedef Documentation

32.21.2.1 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

32.22 gko::stop::Criterion Class Reference

The Criterion class is a base class for all stopping criteria.

`#include <ginkgo/core/stop/criterion.hpp>`

Classes

- class Updater

  The Updater class serves for convenient argument passing to the Criterion's check function.

Public Member Functions

- Updater update ()

  Returns the updater object.
- bool check (uint8 stoppingId, bool setFinalized, Array< stopping_status > *stop_status, bool *one_changed, const Updater &updater)

  This checks whether convergence was reached for a certain criterion.

32.22.1 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.

32.22.2 Member Function Documentation

32.22.2.1 check()

```
bool gko::stop::Criterion::check (
            uint8 stoppingId,
            bool setFinalized,
            Array< stopping_status > * stop_status,
            bool * one_changed,
            const Updater & updater )  [inline]
```

This checks whether convergence was reached for a certain criterion.

The actual implantation of the criterion goes here.

Parameters

stoppingId	id of the stopping criterion
setFinalized	Controls if the current version should count as finalized or not
stop_status	status of the stopping criterion
one_changed	indicates if one vector's status changed
updater	the Updater object containing all the information

Returns

whether convergence was completely reached

```
153     {
154         this->template log<log::Logger::criterion_check_started>(
155             this, updater.num_iterations_, updater.residual_,
156             updater.residual_norm_, updater.solution_, stoppingId,
157             setFinalized);
158         auto all_converged = this->check_impl(
159             stoppingId, setFinalized, stop_status, one_changed, updater);
160         this->template log<log::Logger::criterion_check_completed>(
161             this, updater.num_iterations_, updater.residual_,
162             updater.residual_norm_, updater.solution_, stoppingId, setFinalized,
163             stop_status, *one_changed, all_converged);
164         return all_converged;
165     }
```

Referenced by gko::stop::Criterion::Updater::check().

32.22.2.2 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

32.23 gko::log::criterion_data Struct Reference

Struct representing Criterion related data.

`#include <ginkgo/core/log/record.hpp>`

32.23.1 Detailed Description

Struct representing Criterion related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.24 gko::stop::CriterionArgs Struct Reference

This struct is used to pass parameters to the EnableDefaultCriterionFactoryCriterionFactory::generate() method.

`#include <ginkgo/core/stop/criterion.hpp>`

32.24.1 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

32.25 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 cusparse

  cusparse 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 > 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.
- void sort_by_column_index ()

  Sorts all (value, col_idx) pairs in each row by column index.
- value_type * get_values () noexcept

  Returns the values of the matrix.

- const value_type * get_const_values () const noexcept

  Returns the values of the matrix.
- index_type * get_col_idxs () noexcept

  Returns the column indexes of the matrix.
- const index_type * get_const_col_idxs () const noexcept

  Returns the column indexes of the matrix.
- index_type * get_row_ptrs () noexcept

  Returns the row pointers of the matrix.
- const index_type * get_const_row_ptrs () const noexcept

  Returns the row pointers of the matrix.
- index_type * get_srow () noexcept

  Returns the starting rows.
- const index_type * get_const_srow () const noexcept

  Returns the starting rows.
- size_type get_num_srow_elements () const noexcept

  Returns the number of the srow stored elements (involved warps)
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- std::shared_ptr< strategy_type > get_strategy () const noexcept

  Returns the strategy.
- void set_strategy (std::shared_ptr< strategy_type > strategy)

  Set the strategy.

32.25.1 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

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.25.2 Member Function Documentation

32.25.2.1 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new column permuted object

Implements gko::Permutable< IndexType >.

32.25.2.2 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.

32.25.2.3 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.25.2.4 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.

```
741 { return col_idxs_.get_data(); }
```

References gko::Array< ValueType >::get_data().

32.25.2.5 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().

32.25.2.6 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().

32.25.2.7 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().

32.25.2.8 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().

32.25.2.9 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().

32.25.2.10 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().

32.25.2.11 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().

32.25.2.12 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().

32.25.2.13 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

32.25.2.14 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().

32.25.2.15 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 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< IndexType >.

32.25.2.16 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 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< IndexType >.

32.25.2.17 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.25.2.18 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new permuted object

Implements gko::Permutable< IndexType >.

32.25.2.19 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

strategy	the csr strategy

32.25.2.20 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.

32.25.2.21 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Csr< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/coo.hpp
- ginkgo/core/matrix/csr.hpp

32.26 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.

32.26.1 Detailed Description

CublasError is thrown when a cuBLAS routine throws a non-zero error code.

32.26.2 Constructor & Destructor Documentation

32.26.2.1 CublasError()

```
gko::CublasError::CublasError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a cuBLAS error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the cuBLAS routine that failed
error_code	The resulting cuBLAS error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.27 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.

32.27.1 Detailed Description

CudaError is thrown when a CUDA routine throws a non-zero error code.

32.27.2 Constructor & Destructor Documentation

32.27.2.1 CudaError()

```
gko::CudaError::CudaError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a CUDA error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the CUDA routine that failed
error_code	The resulting CUDA error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.28 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.

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.

32.28.1 Detailed Description

This is the Executor subclass which represents the CUDA device.

32.28.2 Member Function Documentation

32.28.2.1 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

device_id	the CUDA device id of this device
master	an executor on the host that is used to invoke the device kernels

32.28.2.2 get_cublas_handle()

```
cublasContext* gko::CudaExecutor::get_cublas_handle ( ) const  [inline]
```

Get the cublas handle for this executor.

Returns

the cublas handle (cublasContext*) for this executor

```
990 { return cublas_handle_.get(); }
```

32.28.2.3 get_cusparse_handle()

```
cusparseContext* gko::CudaExecutor::get_cusparse_handle ( ) const  [inline]
```

Get the cusparse handle for this executor.

Returns

the cusparse handle (cusparseContext*) for this executor

32.28.2.4 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.

32.28.2.5 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.

32.28.2.6 run()

```
void gko::CudaExecutor::run (
            const Operation & op ) const  [override], [virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implements gko::Executor.

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

32.29 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.

32.29.1 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.

32.29.2 Member Function Documentation

32.29.2.1 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

nnz	the number of nonzeros

Returns

the size of srow

Implements gko::matrix::Csr< ValueType, IndexType >::strategy_type.

32.29.2.2 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.

32.29.2.3 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.30 gko::CusparseError Class Reference

CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.

`#include <ginkgo/core/base/exception.hpp>`

Public Member Functions

- CusparseError (const std::string &file, int line, const std::string &func, int64 error_code)
  Initializes a cuSPARSE error.

32.30.1 Detailed Description

CusparseError is thrown when a cuSPARSE routine throws a non-zero error code.

32.30.2 Constructor & Destructor Documentation

32.30.2.1 CusparseError()

```
gko::CusparseError::CusparseError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a cuSPARSE error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the cuSPARSE routine that failed
error_code	The resulting cuSPARSE error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.31 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.

32.31.1 Detailed Description

template<typename S, typename R>
struct gko::default_converter< S, R >

Used to convert objects of type `S` to objects of type `R` using static_cast.

Template Parameters

S	source type
R	result type

32.31.2 Member Function Documentation

32.31.2.1 operator()()

```
template<typename S , typename R >
R gko::default_converter< S, R >::operator() (
             S val )  [inline]
```

Converts the object to result type.

Parameters

val	the object to convert

Returns

the converted object

The documentation for this struct was generated from the following file:

- ginkgo/core/base/math.hpp

32.32 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 > 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.
- 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 > *inverse_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 > *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< int32 > *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< int64 > *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.
- value_type * get_values () noexcept

  Returns a pointer to the array of values of the matrix.
- const value_type * get_const_values () const noexcept

  Returns a pointer to the array of values of the matrix.
- size_type get_stride () const noexcept

  Returns the stride of the matrix.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- value_type & at (size_type row, size_type col) noexcept

  Returns a single element of the matrix.
- value_type at (size_type row, size_type col) const noexcept

  Returns a single element of the matrix.
- ValueType & at (size_type idx) noexcept

  Returns a single element of the matrix.
- ValueType at (size_type idx) const noexcept

  Returns a single element of the matrix.
- void scale (const LinOp *alpha)

  Scales the matrix with a scalar (aka: BLAS scal).
- void add_scaled (const LinOp *alpha, const LinOp *b)

  Adds `b` scaled by `alpha` to the matrix (aka: BLAS axpy).
- void compute_dot (const LinOp *b, LinOp *result) const

  Computes the column-wise dot product of this matrix and `b`.
- void compute_norm2 (LinOp *result) const

  Computes the Euclidian (L^2) norm of this matrix.
- std::unique_ptr< Dense > create_submatrix (const span &rows, const span &columns, const size_type stride)

  Create a submatrix from the original matrix.

Static Public Member Functions

- static std::unique_ptr< Dense > create_with_config_of (const Dense *other)

  Creates a Dense matrix with the configuration of another Dense matrix.

32.32.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::Dense< ValueType >

Dense is a matrix format which explicitly stores all values of the matrix.

The values are stored in row-major format (values belonging to the same row appear consecutive in the memory). Optionally, rows can be padded for better memory access.

Template Parameters

ValueType	precision of matrix elements

Note

While this format is not very useful for storing sparse matrices, it is often suitable to store vectors, and sets of vectors.

32.32.2 Member Function Documentation

32.32.2.1 add_scaled()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::add_scaled (
            const LinOp * alpha,
            const LinOp * b )  [inline]
```

Adds `b` scaled by `alpha` to the matrix (aka: BLAS axpy).

Parameters

alpha	If alpha is 1x1 Dense matrix, the entire matrix is scaled by alpha. If it is a Dense row vector of values, then i-th column of the matrix is scaled with the i-th element of alpha (the number of columns of alpha has to match the number of columns of the matrix).
b	a matrix of the same dimension as this

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.32.2.2 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

idx	a linear index of the requested element (ignoring the stride)

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

32.32.2.3 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

idx	a linear index of the requested element (ignoring the stride)

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

32.32.2.4 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

row	the row of the requested element
col	the column of the requested element

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

32.32.2.5 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

row	the row of the requested element
col	the column of the requested element

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

Referenced by gko::initialize().

32.32.2.6 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new column permuted object

Implements gko::Permutable< int32 >.

32.32.2.7 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new column permuted object

Implements gko::Permutable< int64 >.

32.32.2.8 compute_dot()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::compute_dot (
            const LinOp * b,
            LinOp * result ) const  [inline]
```

Computes the column-wise dot product of this matrix and b.

The conjugate of this is taken.

Parameters

b	a Dense matrix of same dimension as this
result	a Dense row vector, used to store the dot product (the number of column in the vector must match the number of columns of this)

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.32.2.9 compute_norm2()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::compute_norm2 (
            LinOp * result ) const  [inline]
```

Computes the Euclidian (L^2) norm of this matrix.

Parameters

result	a Dense row vector, used to store the norm (the number of columns in the vector must match the number of columns of this)

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.32.2.10 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.

32.32.2.11 create_submatrix()

```
template<typename ValueType = default_precision>
std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::create_submatrix (
            const span & rows,
            const span & columns,
            const size_type stride )  [inline]
```

Create a submatrix from the original matrix.

Warning: defining stride for this create_submatrix method might cause wrong memory access. Better use the create_submatrix(rows, columns) method instead.

Parameters

rows	row span
columns	column span
stride	stride of the new submatrix.

References gko::span::begin, gko::PolymorphicObject::get_executor(), gko::matrix::Dense< ValueType >::get_↩ stride(), gko::matrix::Dense< ValueType >::get_values(), and gko::Array< ValueType >::view().

32.32.2.12 create_with_config_of()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Dense> gko::matrix::Dense< ValueType >::create_with_config_of (
            const Dense< ValueType > * other )  [inline], [static]
```

Creates a Dense matrix with the configuration of another Dense matrix.

Parameters

other	The other matrix whose configuration needs to copied.

32.32.2.13 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.32.2.14 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().

32.32.2.15 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().

32.32.2.16 get_stride()

```
template<typename ValueType = default_precision>
size_type gko::matrix::Dense< ValueType >::get_stride ( ) const  [inline], [noexcept]
```

Returns the stride of the matrix.

Returns

the stride of the matrix.

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

32.32.2.17 get_values()

```
template<typename ValueType = default_precision>
value_type* gko::matrix::Dense< ValueType >::get_values ( )  [inline], [noexcept]
```

Returns a pointer to the array of values of the matrix.

Returns

the pointer to the array of values

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Dense< ValueType >::create_submatrix().

32.32.2.18 inverse_column_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_column_permute (
            const Array< int32 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< int32 >.

32.32.2.19 inverse_column_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_column_permute (
            const Array< int64 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< int64 >.

32.32.2.20 inverse_row_permute() [1/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_row_permute (
            const Array< int32 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< int32 >.

32.32.2.21 inverse_row_permute() [2/2]

```
template<typename ValueType = default_precision>
std::unique_ptr<LinOp> gko::matrix::Dense< ValueType >::inverse_row_permute (
            const Array< int64 > * inverse_permutation_indices ) const  [override], [virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

Returns

a pointer to the new inverse permuted object

Implements gko::Permutable< int64 >.

32.32.2.22 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new permuted object

Implements gko::Permutable< int32 >.

32.32.2.23 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

Returns

a pointer to the new permuted object

Implements gko::Permutable< int64 >.

32.32.2.24 scale()

```
template<typename ValueType = default_precision>
void gko::matrix::Dense< ValueType >::scale (
            const LinOp * alpha )  [inline]
```

Scales the matrix with a scalar (aka: BLAS scal).

Parameters

alpha	If alpha is 1x1 Dense matrix, the entire matrix is scaled by alpha. If it is a Dense row vector of values, then i-th column of the matrix is scaled with the i-th element of alpha (the number of columns of alpha has to match the number of columns of the matrix).

References gko::PolymorphicObject::get_executor(), and gko::make_temporary_clone().

32.32.2.25 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

32.33 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.
- 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.

32.33.1 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

ValueType	precision of matrix elements
IndexType	precision of matrix indexes of a CSR matrix the diagonal is applied or converted to.

32.33.2 Member Function Documentation

32.33.2.1 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.

32.33.2.2 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.

```
117     {
118         return values_.get_const_data();
119     }
```

References gko::Array< ValueType >::get_const_data().

32.33.2.3 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().

32.33.2.4 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

b	the input vector(s) on which the diagonal matrix is applied
x	the output vector(s) where the result is stored

32.33.2.5 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

32.34 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.

32.34.1 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.

32.34.2 Member Function Documentation

32.34.2.1 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

diag	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

32.35 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.

32.35.1 Detailed Description

template<size_type Dimensionality, typename DimensionType = size_type>
struct gko::dim< Dimensionality, DimensionType >

A type representing the dimensions of a multidimensional object.

Template Parameters

Dimensionality	number of dimensions of the object
DimensionType	datatype used to represent each dimension

32.35.2 Constructor & Destructor Documentation

32.35.2.1 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

size	the size of each dimension

32.35.2.2 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

first	first dimension
rest	other dimensions

32.35.3 Member Function Documentation

32.35.3.1 operator bool()

```
template<size_type Dimensionality, typename DimensionType = size_type>
constexpr gko::dim< Dimensionality, DimensionType >::operator bool ( ) const  [inline], [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

32.35.3.2 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

dimension	the requested dimension

Returns

the `dimension`-th dimension

32.35.3.3 operator[]() [2/2]

```
template<size_type Dimensionality, typename DimensionType = size_type>
dimension_type& gko::dim< Dimensionality, DimensionType >::operator[] (
            const size_type & dimension )  [inline], [noexcept]
```

32.35.4 Friends And Related Function Documentation

32.35.4.1 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

x	first object
y	second object

Returns

a dim object representing the size of the tensor product `x * y`

32.35.4.2 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

x	first object
y	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

32.36 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.

32.36.1 Detailed Description

DimensionMismatch is thrown if an operation is being applied to LinOps of incompatible size.

32.36.2 Constructor & Destructor Documentation

32.36.2.1 DimensionMismatch()

```
gko::DimensionMismatch::DimensionMismatch (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & first_name,
            size_type first_rows,
            size_type first_cols,
            const std::string & second_name,
            size_type second_rows,
            size_type second_cols,
            const std::string & clarification )  [inline]
```

Initializes a dimension mismatch error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The function name where the error occurred
first_name	The name of the first operator
first_rows	The output dimension of the first operator
first_cols	The input dimension of the first operator
second_name	The name of the second operator
second_rows	The output dimension of the second operator
second_cols	The input dimension of the second operator

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.37 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.
- value_type * get_values () noexcept

  Returns the values of the matrix.
- const value_type * get_const_values () const noexcept

  Returns the values of the matrix.
- index_type * get_col_idxs () noexcept

  Returns the column indexes of the matrix.
- const index_type * get_const_col_idxs () const noexcept

  Returns the column indexes of the matrix.
- size_type get_num_stored_elements_per_row () const noexcept

  Returns the number of stored elements per row.
- size_type get_stride () const noexcept

  Returns the stride of the matrix.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- value_type & val_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th non-zero element of the `row`-th row .
- value_type val_at (size_type row, size_type idx) const noexcept

  Returns the `idx`-th non-zero element of the `row`-th row .
- index_type & col_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th column index of the `row`-th row .
- index_type col_at (size_type row, size_type idx) const noexcept

  Returns the `idx`-th column index of the `row`-th row .

32.37.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Ell< ValueType, IndexType >

ELL is a matrix format where stride with explicit zeros is used such that all rows have the same number of stored elements.

The number of elements stored in each row is the largest number of nonzero elements in any of the rows (obtainable through get_num_stored_elements_per_row() method). This removes the need of a row pointer like in the CSR format, and allows for SIMD processing of the distinct rows. For efficient processing, the nonzero elements and the corresponding column indices are stored in column-major fashion. The columns are padded to the length by user-defined stride parameter whose default value is the number of rows of the matrix.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.37.2 Member Function Documentation

32.37.2.1 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

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
220     {
221         return this->get_const_col_idxs()[this->linearize_index(row, idx)];
222     }
```

References gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs().

32.37.2.2 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

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::matrix::Ell< ValueType, IndexType >::get_col_idxs().

32.37.2.3 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.37.2.4 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Ell< ValueType, IndexType >::get_col_idxs ( ) [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Ell< ValueType, IndexType >::col_at().

32.37.2.5 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Ell< ValueType, IndexType >::get_const_col_idxs ( ) const  [inline],
[noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

Referenced by gko::matrix::Ell< ValueType, IndexType >::col_at().

32.37.2.6 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().

32.37.2.7 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().

32.37.2.8 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.

32.37.2.9 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.

32.37.2.10 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().

32.37.2.11 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Ell< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.37.2.12 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

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_const_data().

32.37.2.13 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

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

References gko::Array< ValueType >::get_data().

32.37.2.14 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Ell< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp
- ginkgo/core/matrix/ell.hpp

32.38 gko::enable_parameters_type< ConcreteParametersType, Factory > Struct Template Reference

The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.

```
#include <ginkgo/core/base/abstract_factory.hpp>
```

Public Member Functions

- std::unique_ptr< Factory > on (std::shared_ptr< const Executor > exec) const

  Creates a new factory on the specified executor.

32.38.1 Detailed Description

template<typename ConcreteParametersType, typename Factory>
struct gko::enable_parameters_type< ConcreteParametersType, Factory >

The enable_parameters_type mixin is used to create a base implementation of the factory parameters structure.

It provides only the on() method which can be used to instantiate the factory give the parameters stored in the structure.

Template Parameters

ConcreteParametersType	the concrete parameters type which is being implemented [CRTP parameter]
Factory	the concrete factory for which these parameters are being used

32.38.2 Member Function Documentation

32.38.2.1 on()

```
template<typename ConcreteParametersType, typename Factory>
std::unique_ptr<Factory> gko::enable_parameters_type< ConcreteParametersType, Factory >::on (
            std::shared_ptr< const Executor > exec ) const  [inline]
```

Creates a new factory on the specified executor.

Parameters

exec	the executor where the factory will be created

Returns

a new factory instance

The documentation for this struct was generated from the following file:

- ginkgo/core/base/abstract_factory.hpp

32.39 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>`

32.39.1 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

AbstractObject	the abstract class which is being implemented [CRTP parameter]
PolymorphicBase	parent of AbstractObject in the polymorphic hierarchy, has to be a subclass of polymorphic object

See also

EnablePolymorphicObject for creating a concrete subclass of PolymorphicObject.

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

32.40 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>`

32.40.1 Detailed Description

template<typename ConcreteType>
class gko::EnableCreateMethod< ConcreteType >

This mixin implements a static `create()` method on `ConcreteType` that dynamically allocates the memory, uses the passed-in arguments to construct the object, and returns an std::unique_ptr to such an object.

Template Parameters

ConcreteObject	the concrete type for which `create()` is being implemented [CRTP parameter]

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

32.41 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.

32.41.1 Detailed Description

template<typename ConcreteFactory, typename ProductType, typename ParametersType, typename PolymorphicBase>
class gko::EnableDefaultFactory< ConcreteFactory, ProductType, ParametersType, PolymorphicBase >

This mixin provides a default implementation of a concrete factory.

It implements all the methods of AbstractFactory and PolymorphicObject. Its implementation of the generate_impl() method delegates the creation of the product by calling the `ProductType::ProductType(const ConcreteFactory *, const components_type &)` constructor. The factory also supports parameters by using the `ParametersType` structure, which is defined by the user.

For a simple example, see IntFactory in `core/test/base/abstract_factory.cpp`.

Template Parameters

ConcreteFactory	the concrete factory which is being implemented [CRTP parameter]
ProductType	the concrete type of products which this factory produces, has to be a subclass of PolymorphicBase::abstract_product_type
ParametersType	a type representing the parameters of the factory, has to inherit from the enable_parameters_type mixin
PolymorphicBase	parent of ConcreteFactory in the polymorphic hierarchy, has to be a subclass of AbstractFactory

32.41.2 Member Function Documentation

32.41.2.1 create()

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
static parameters_type gko::EnableDefaultFactory< ConcreteFactory, ProductType, Parameters
Type, PolymorphicBase >::create ( )  [inline], [static]
```

Creates a new ParametersType object which can be used to instantiate a new ConcreteFactory.

This method does not construct the factory directly, but returns a new parameters_type object, which can be used to set the parameters of the factory. Once the parameters have been set, the parameters_type::on() method can be used to obtain an instance of the factory with those parameters.

Returns

a default parameters_type object

32.41.2.2 get_parameters()

```
template<typename ConcreteFactory , typename ProductType , typename ParametersType , typename
PolymorphicBase >
const parameters_type& gko::EnableDefaultFactory< ConcreteFactory, ProductType, Parameters↩
Type, PolymorphicBase >::get_parameters ( ) const  [inline], [noexcept]
```

Returns the parameters of the factory.

Returns

the parameters of the factory

The documentation for this class was generated from the following file:

- ginkgo/core/base/abstract_factory.hpp

32.42 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

32.42.1 Detailed Description

template<typename ConcreteLinOp, typename PolymorphicBase = LinOp>
class gko::EnableLinOp< ConcreteLinOp, PolymorphicBase >

The EnableLinOp mixin can be used to provide sensible default implementations of the majority of the LinOp and PolymorphicObject interface.

The goal of the mixin is to facilitate the development of new LinOp, by enabling the implementers to focus on the important parts of their operator, while the library takes care of generating the trivial utility functions. The mixin will provide default implementations for the entire PolymorphicObject interface, including a default implementation of `copy_from` between objects of the new LinOp type. It will also hide the default LinOp::apply() methods with versions that preserve the static type of the object.

Implementers of new LinOps are required to specify only the following aspects:

1. Creation of the LinOp: This can be facilitated via either EnableCreateMethod mixin (used mostly for matrix formats), or GKO_ENABLE_LIN_OP_FACTORY macro (used for operators created from other operators, like preconditioners and solvers).
2. Application of the LinOp: Implementers have to override the two overloads of the LinOp::apply_impl() virtual methods.

Template Parameters

ConcreteLinOp	the concrete LinOp which is being implemented [CRTP parameter]
PolymorphicBase	parent of ConcreteLinOp in the polymorphic hierarchy, has to be a subclass of LinOp

The documentation for this class was generated from the following file:

- ginkgo/core/base/lin_op.hpp

32.43 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.

32.43.1 Detailed Description

template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
class gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >

EnableLogging is a mixin which should be inherited by any class which wants to enable logging.

All the received events are passed to the loggers this class contains.

Template Parameters

ConcreteLoggable	the object being logged [CRTP parameter]
PolymorphicBase	the polymorphic base of this class. By default it is Loggable. Change it if you want to use a new superclass of `Loggable` as polymorphic base of this class.

32.43.2 Member Function Documentation

32.43.2.1 add_logger()

```
template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
void gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >::add_logger (
            std::shared_ptr< const Logger > logger )  [inline], [override], [virtual]
```

Adds a new logger to the list of subscribed loggers.

Parameters

logger	the logger to add

Implements gko::log::Loggable.

```
524     {
525         loggers_.push_back(logger);
526     }
```

32.43.2.2 remove_logger()

```
template<typename ConcreteLoggable, typename PolymorphicBase = Loggable>
void gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >::remove_logger (
            const Logger * logger )  [inline], [override], [virtual]
```

Removes a logger from the list of subscribed loggers.

Parameters

logger	the logger to remove

Note

The comparison is done using the logger's object unique identity. Thus, two loggers constructed in the same way are not considered equal.

Implements gko::log::Loggable.

The documentation for this class was generated from the following file:

- ginkgo/core/log/logger.hpp

32.44 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.

32.44.1 Detailed Description

template<typename ConcreteType, typename ResultType = ConcreteType>
class gko::EnablePolymorphicAssignment< ConcreteType, ResultType >

This mixin is used to enable a default PolymorphicObject::copy_from() implementation for objects that have implemented conversions between them.

The requirement is that there is either a conversion constructor from `ConcreteType` in `ResultType`, or a conversion operator to `ResultType` in `ConcreteType`.

Template Parameters

ConcreteType	the concrete type from which the copy_from is being enabled [CRTP parameter]
ResultType	the type to which copy_from is being enabled

32.44.2 Member Function Documentation

32.44.2.1 convert_to()

```
template<typename ConcreteType, typename ResultType = ConcreteType>
void gko::EnablePolymorphicAssignment< ConcreteType, ResultType >::convert_to (
            result_type * result ) const  [inline], [override], [virtual]
```

Converts the implementer to an object of type result_type.

Parameters

result	the object used to store the result of the conversion

Implements gko::ConvertibleTo< ResultType >.

32.44.2.2 move_to()

```
template<typename ConcreteType, typename ResultType = ConcreteType>
void gko::EnablePolymorphicAssignment< ConcreteType, ResultType >::move_to (
            result_type * result )  [inline], [override], [virtual]
```

Converts the implementer to an object of type result_type by moving data from this object.

This method is used when the implementer is a temporary object, and move semantics can be used.

Parameters

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implements gko::ConvertibleTo< ResultType >.

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

32.45 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>`

32.45.1 Detailed Description

template<typename ConcreteObject, typename PolymorphicBase = PolymorphicObject>
class gko::EnablePolymorphicObject< ConcreteObject, PolymorphicBase >

This mixin inherits from (a subclass of) PolymorphicObject and provides a base implementation of a new concrete polymorphic object.

The mixin changes parameter and return types of appropriate public methods of PolymorphicObject in the same way EnableAbstractPolymorphicObject does. In addition, it also provides default implementations of PolymorphicObject's vritual methods by using the *executor default constructor* and the assignment operator of ConcreteObject. Consequently, the following is a minimal example of PolymorphicObject:

```
 {c++}
struct MyObject : EnablePolymorphicObject<MyObject> {
    MyObject(std::shared_ptr<const Executor> exec)
        : EnablePolymorphicObject<MyObject>(std::move(exec))
    {}
};
```

In a way, this mixin can be viewed as an extension of default constructor/destructor/assignment operators.

Note

This mixin does not enable copying the polymorphic object to the object of the same type (i.e. it does not implement the ConvertibleTo<ConcreteObject> interface). To enable a default implementation of this interface see the EnablePolymorphicAssignment mixin.

Template Parameters

ConcreteObject	the concrete type which is being implemented [CRTP parameter]
PolymorphicBase	parent of ConcreteObject in the polymorphic hierarchy, has to be a subclass of polymorphic object

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

32.46 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.

32.46.1 Detailed Description

The Error class is used to report exceptional behaviour in library functions.

Ginkgo uses C++ exception mechanism to this end, and the Error class represents a base class for all types of errors. The exact list of errors which could occur during the execution of a certain library routine is provided in the documentation of that routine, along with a short description of the situation when that error can occur. During runtime, these errors can be detected by using standard C++ try-catch blocks, and a human-readable error description can be obtained by calling the Error::what() method.

As an example, trying to compute a matrix-vector product with arguments of incompatible size will result in a DimensionMismatch error, which is demonstrated in the following program.

```
#include <ginkgo.h>
#include <iostream>
using namespace gko;
int main()
{
    auto omp = create<OmpExecutor>();
    auto A = randn_fill<matrix::Csr<float»(5, 5, 0f, 1f, omp);
    auto x = fill<matrix::Dense<float»(6, 1, 1f, omp);
    try {
        auto y = apply(A.get(), x.get());
    } catch(Error e) {
        // an error occured, write the message to screen and exit
        std::cout « e.what() « std::endl;
        return -1;
    }
    return 0;
}
```

32.46.2 Constructor & Destructor Documentation

32.46.2.1 Error()

```
gko::Error::Error (
            const std::string & file,
            int line,
            const std::string & what )  [inline]
```

Initializes an error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
what	The error message

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.47 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 >
  void run (const ClosureOmp &op_omp, const ClosureCuda &op_cuda, const ClosureHip &op_hip) 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.

32.47.1 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;
- 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.

32.47.2 Member Function Documentation

32.47.2.1 alloc()

```
template<typename T >
T* gko::Executor::alloc (
            size_type num_elems ) const  [inline]
```

Allocates memory in this Executor.

Template Parameters

T	datatype to allocate

Parameters

num_elems	number of elements of type T to allocate

Exceptions

AllocationError	if the allocation failed

Returns

pointer to allocated memory

32.47.2.2 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

T	datatype to copy

Parameters

num_elems	number of elements of type T to copy
src_ptr	pointer to a block of memory containing the data to be copied
dest_ptr	pointer to an allocated block of memory where the data will be copied to

References copy_from().

32.47.2.3 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

T	datatype to copy

Parameters

src_exec	Executor from which the memory will be copied
num_elems	number of elements of type T to copy
src_ptr	pointer to a block of memory containing the data to be copied
dest_ptr	pointer to an allocated block of memory where the data will be copied to

Referenced by copy().

32.47.2.4 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

T	datatype to copy

Parameters

ptr	the pointer to the element to be copied

Returns

the value stored at ptr

References get_master().

32.47.2.5 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

ptr	pointer to the allocated memory block

32.47.2.6 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::HipExecutor, gko::CudaExecutor, and gko::OmpExecutor.

32.47.2.7 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::HipExecutor, gko::CudaExecutor, and gko::OmpExecutor.

Referenced by copy_val_to_host().

32.47.2.8 run() [1/2]

```
template<typename ClosureOmp , typename ClosureCuda , typename ClosureHip >
void gko::Executor::run (
             const ClosureOmp & op_omp,
             const ClosureCuda & op_cuda,
             const ClosureHip & op_hip ) const  [inline]
```

Runs one of the passed in functors, depending on the Executor type.

Template Parameters

ClosureOmp	type of op_omp
ClosureCuda	type of op_cuda
ClosureHip	type of op_hip

Parameters

op_omp	functor to run in case of a OmpExecutor or ReferenceExecutor
op_cuda	functor to run in case of a CudaExecutor
op_hip	functor to run in case of a HipExecutor

References run().

32.47.2.9 run() [2/2]

```
virtual void gko::Executor::run (
             const Operation & op ) const  [pure virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implemented in gko::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

32.48 gko::log::executor_data Struct Reference

Struct representing Executor related data.

`#include <ginkgo/core/log/record.hpp>`

32.48.1 Detailed Description

Struct representing Executor related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.49 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.

32.49.1 Detailed Description

template<typename T>
class gko::executor_deleter< T >

This is a deleter that uses an executor's `free` method to deallocate the data.

Template Parameters

T	the type of object being deleted

32.49.2 Constructor & Destructor Documentation

32.49.2.1 executor_deleter()

```
template<typename T >
gko::executor_deleter< T >::executor_deleter (
            std::shared_ptr< const Executor > exec )  [inline], [explicit]
```

Creates a new deleter.

Parameters

exec	the executor used to free the data

32.49.3 Member Function Documentation

32.49.3.1 operator()()

```
template<typename T >
void gko::executor_deleter< T >::operator() (
            pointer ptr ) const  [inline]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

32.50 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.

32.50.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Fcg< ValueType >

FCG or the flexible conjugate gradient method is an iterative type Krylov subspace method which is suitable for symmetric positive definite methods.

Though this method performs very well for symmetric positive definite matrices, it is in general not suitable for general matrices.

In contrast to the standard CG based on the Polack-Ribiere formula, the flexible CG uses the Fletcher-Reeves formula for creating the orthonormal vectors spanning the Krylov subspace. This increases the computational cost of every Krylov solver iteration but allows for non-constant preconditioners.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of FCG are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

32.50.2 Member Function Documentation

32.50.2.1 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; }
```

32.50.2.2 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.

32.50.2.3 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

32.50.2.4 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)

32.50.2.5 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

other	the new stopping criterion factory

32.50.2.6 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

32.51 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.

32.51.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Gmres< ValueType >

GMRES or the generalized minimal residual method is an iterative type Krylov subspace method which is suitable for nonsymmetric linear systems.

The implementation in Ginkgo makes use of the merged kernel to make the best use of data locality. The inner operations in one iteration of GMRES are merged into 2 separate steps.

Template Parameters

ValueType	precision of matrix elements

32.51.2 Member Function Documentation

32.51.2.1 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; }
```

32.51.2.2 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.

32.51.2.3 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

32.51.2.4 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

32.51.2.5 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)

32.51.2.6 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

other	the new krylov dimension

32.51.2.7 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

other	the new stopping criterion factory

32.51.2.8 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

32.52 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.

32.52.1 Detailed Description

HipblasError is thrown when a hipBLAS routine throws a non-zero error code.

32.52.2 Constructor & Destructor Documentation

32.52.2.1 HipblasError()

```
gko::HipblasError::HipblasError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a hipBLAS error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the hipBLAS routine that failed
error_code	The resulting hipBLAS error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.53 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.

32.53.1 Detailed Description

HipError is thrown when a HIP routine throws a non-zero error code.

32.53.2 Constructor & Destructor Documentation

32.53.2.1 HipError()

```
gko::HipError::HipError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a HIP error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the HIP routine that failed
error_code	The resulting HIP error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.54 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.
- hipsparseContext * get_hipsparse_handle () const

  Get the hipsparse handle for this executor.

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.

32.54.1 Detailed Description

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

32.54.2 Member Function Documentation

32.54.2.1 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

device_id	the HIP device id of this device
master	an executor on the host that is used to invoke the device kernels

32.54.2.2 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

32.54.2.3 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

32.54.2.4 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.

32.54.2.5 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.

32.54.2.6 run()

```
void gko::HipExecutor::run (
            const Operation & op ) const  [override], [virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implements gko::Executor.

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

32.55 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.

32.55.1 Detailed Description

HipsparseError is thrown when a hipSPARSE routine throws a non-zero error code.

32.55.2 Constructor & Destructor Documentation

32.55.2.1 HipsparseError()

```
gko::HipsparseError::HipsparseError (
            const std::string & file,
            int line,
            const std::string & func,
            int64 error_code )  [inline]
```

Initializes a hipSPARSE error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the hipSPARSE routine that failed
error_code	The resulting hipSPARSE error code

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.56 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.
- value_type * get_ell_values () noexcept

  Returns the values of the ell part.
- const value_type * get_const_ell_values () const noexcept

  Returns the values of the ell part.
- index_type * get_ell_col_idxs () noexcept

  Returns the column indexes of the ell part.
- const index_type * get_const_ell_col_idxs () const noexcept

  Returns the column indexes of the ell part.
- size_type get_ell_num_stored_elements_per_row () const noexcept

  Returns the number of stored elements per row of ell part.
- size_type get_ell_stride () const noexcept

  Returns the stride of the ell part.

- size_type get_ell_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the ell part.
- value_type & ell_val_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th non-zero element of the `row`-th row in the ell part.
- value_type ell_val_at (size_type row, size_type idx) const noexcept

  Returns the `idx`-th non-zero element of the `row`-th row in the ell part.
- index_type & ell_col_at (size_type row, size_type idx) noexcept

  Returns the `idx`-th column index of the `row`-th row in the ell part.
- index_type ell_col_at (size_type row, size_type idx) const noexcept

  Returns the `idx`-th column index of the `row`-th row in the ell part.
- const ell_type * get_ell () const noexcept

  Returns the matrix of the ell part.
- value_type * get_coo_values () noexcept

  Returns the values of the coo part.
- const value_type * get_const_coo_values () const noexcept

  Returns the values of the coo part.
- index_type * get_coo_col_idxs () noexcept

  Returns the column indexes of the coo part.
- const index_type * get_const_coo_col_idxs () const noexcept

  Returns the column indexes of the coo part.
- index_type * get_coo_row_idxs () noexcept

  Returns the row indexes of the coo part.
- const index_type * get_const_coo_row_idxs () const noexcept

  Returns the row indexes of the coo part.
- size_type get_coo_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the coo part.
- const coo_type * get_coo () const noexcept

  Returns the matrix of the coo part.
- size_type get_num_stored_elements () const noexcept

  Returns the number of elements explicitly stored in the matrix.
- std::shared_ptr< strategy_type > get_strategy () const noexcept

  Returns the strategy.
- Hybrid & operator= (const Hybrid &other)

  Copies data from another Hybrid.

32.56.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Hybrid< ValueType, IndexType >

HYBRID is a matrix format which splits the matrix into ELLPACK and COO format.

Achieve the excellent performance with a proper partition of ELLPACK and COO.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.56.2 Member Function Documentation

32.56.2.1 ell_col_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type gko::matrix::Hybrid< ValueType, IndexType >::ell_col_at (
            size_type row,
            size_type idx ) const  [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

```
468     {
469         return ell_->col_at(row, idx);
470     }
```

32.56.2.2 ell_col_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type& gko::matrix::Hybrid< ValueType, IndexType >::ell_col_at (
            size_type row,
            size_type idx )  [inline], [noexcept]
```

Returns the `idx`-th column index of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

32.56.2.3 ell_val_at() [1/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type gko::matrix::Hybrid< ValueType, IndexType >::ell_val_at (
            size_type row,
            size_type idx ) const  [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

32.56.2.4 ell_val_at() [2/2]

```
template<typename ValueType = default_precision, typename IndexType = int32>
value_type& gko::matrix::Hybrid< ValueType, IndexType >::ell_val_at (
            size_type row,
            size_type idx )  [inline], [noexcept]
```

Returns the `idx`-th non-zero element of the `row`-th row in the ell part.

Parameters

row	the row of the requested element
idx	the idx-th stored element of the row

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the OMP results in a runtime error)

32.56.2.5 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.56.2.6 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.

32.56.2.7 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.

32.56.2.8 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.

32.56.2.9 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.

32.56.2.10 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.

32.56.2.11 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

32.56.2.12 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.

32.56.2.13 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

32.56.2.14 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.

32.56.2.15 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.

32.56.2.16 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

32.56.2.17 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

32.56.2.18 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

32.56.2.19 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

32.56.2.20 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

32.56.2.21 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

32.56.2.22 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

32.56.2.23 get_strategy()

```
template<typename ValueType = default_precision, typename IndexType = int32>
std::shared_ptr<strategy_type> gko::matrix::Hybrid< ValueType, IndexType >::get_strategy ( )
const  [inline], [noexcept]
```

Returns the strategy.

Returns

the strategy

32.56.2.24 operator=()

```
template<typename ValueType = default_precision, typename IndexType = int32>
Hybrid& gko::matrix::Hybrid< ValueType, IndexType >::operator= (
            const Hybrid< ValueType, IndexType > & other )  [inline]
```

Copies data from another Hybrid.

Parameters

other	the Hybrid to copy from

Returns

this

32.56.2.25 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.56.2.26 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::write (
            mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp
- ginkgo/core/matrix/hybrid.hpp

32.57 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.

32.57.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::Identity< ValueType >

This class is a utility which efficiently implements the identity matrix (a linear operator which maps each vector to itself).

Thus, objects of the Identity class always represent a square matrix, and don't require any storage for their values. The apply method is implemented as a simple copy (or a linear combination).

Note

This class is useful when composing it with other operators. For example, it can be used instead of a preconditioner in Krylov solvers, if one wants to run a "plain" solver, without using a preconditioner.

Template Parameters

ValueType	precision of matrix elements

32.57.2 Member Function Documentation

32.57.2.1 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.

32.57.2.2 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

32.58 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

32.58.1 Detailed Description

template<typename ValueType = default_precision>
class gko::matrix::IdentityFactory< ValueType >

This factory is a utility which can be used to generate Identity operators.

The factory will generate the Identity matrix with the same dimension as the passed in operator. It will throw an exception if the operator is not square.

Template Parameters

ValueType	precision of matrix elements

32.58.2 Member Function Documentation

32.58.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<IdentityFactory> gko::matrix::IdentityFactory< ValueType >::create (
            std::shared_ptr< const Executor > exec )  [inline], [static]
```

Creates a new Identity factory.

Parameters

exec	the executor where the Identity operator will be stored

Returns

a unique pointer to the newly created factory

```
136     {
137         return std::unique_ptr<IdentityFactory>(
138             new IdentityFactory(std::move(exec)));
139     }
```

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/identity.hpp

32.59 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.

32.59.1 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 triangluar solver are:

- reduction factor = 1e-4
- max iteration = <number of="" rows="" of="" the="" matrix="" given="" to="" the="" solver>=""> Solvers without such criteria can also be used, in which case none are set.

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. ParIlu 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

LSolverType	type of the solver used for the L matrix. Defaults to solver::LowerTrs
USolverType	type of the solver used for the U matrix Defaults to solver::UpperTrs
ReverseApply	default behavior (ReverseApply = false) is first to solve with L (Ly = b) and then with U (Ux = y). When set to true, it will solve first with U, and then with L.
IndexTypeParIlu	Type of the indices when ParIlu is used to generate both L and U factors. Irrelevant otherwise.

32.59.2 Member Function Documentation

32.59.2.1 conj_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 >::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.

```
193     {
194         std::unique_ptr<transposed_type> transposed{
195             new transposed_type{this->get_executor()}};
196         transposed->set_size(gko::transpose(this->get_size()));
197         transposed->l_solver_ =
198             share(as<typename u_solver_type::transposed_type>(
199                 this->get_u_solver()->conj_transpose()));
200         transposed->u_solver_ =
201             share(as<typename l_solver_type::transposed_type>(
202                 this->get_l_solver()->conj_transpose()));
203
204         return std::move(transposed);
205     }
```

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().

32.59.2.2 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().

32.59.2.3 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().

32.59.2.4 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

32.60 gko::factorization::Ilu< 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

32.60.1 Detailed Description

template<typename ValueType = gko::default_precision, typename IndexType = gko::int32>
class gko::factorization::Ilu< 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 $\mathcal{S}(L+U) = \mathcal{S}(A)$ fulfilling $LU = A$ at every non-zero location of A.

Template Parameters

ValueType	Type of the values of all matrices used in this class
IndexType	Type of the indices of all matrices used in this class

The documentation for this class was generated from the following file:

- ginkgo/core/factorization/ilu.hpp

32.61 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 (float percent=0.8, float ratio=0.0001)

  Creates a imbalance_bounded_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > *row_nnz) const override

  Computes the number of stored elements per row of the ell part.

32.61.1 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.

32.61.2 Member Function Documentation

32.61.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit::compute_ell_↩
num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::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().

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp

32.62 gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit Class Reference

imbalance_limit is a strategy_type which decides the number of stored elements per row of the ell part according to the percent.

`#include <ginkgo/core/matrix/hybrid.hpp>`

Public Member Functions

- imbalance_limit (float percent=0.8)
  Creates a imbalance_limit strategy.
- size_type compute_ell_num_stored_elements_per_row (Array< size_type > *row_nnz) const override
  Computes the number of stored elements per row of the ell part.

32.62.1 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.

32.62.2 Constructor & Destructor Documentation

32.62.2.1 imbalance_limit()

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::imbalance_limit (
            float percent = 0.8 )  [inline], [explicit]
```

Creates a imbalance_limit strategy.

Parameters

percent	the row_nnz[floor(num_rows∗percent)] is the number of stored elements per row of the ell part

32.62.3 Member Function Documentation

32.62.3.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_↩
stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::Array< ValueType >::get_data(), and gko::Array< ValueType >::get_num_elems().

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().

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp

32.63 gko::solver::Ir< ValueType > Class Template Reference

Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.

```
#include <ginkgo/core/solver/ir.hpp>
```

Public Member Functions

- std::shared_ptr< const LinOp > get_system_matrix () const

  Returns the system operator (matrix) of the linear system.
- std::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.

32.63.1 Detailed Description

template<typename ValueType = default_precision>
class gko::solver::Ir< ValueType >

Iterative refinement (IR) is an iterative method that uses another coarse method to approximate the error of the current solution via the current residual.

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 - solution` (with `x` being the exact solution) can be obtained as the solution to the residual equation `Ae = residual`, since `A e = Ax - A solution = b - A solution = residual`. Then, the real solution is computed as `x = relaxation_factor * solution + e`. Instead of accurately solving the residual equation `Ae = residual`, the solution of the system `e` can be approximated to obtain the approximation `error` using a coarse method `solver`, which is used to update `solution`, and the entire process is repeated with the updated `solution`. This yields the iterative refinement method:

```
solution = initial_guess
while not converged:
    residual = b - A solution
    error = solver(A, residual)
    solution = solution + 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 - error | <= c | e |`, iterative refinement will converge with a convergence rate of `c`. Indeed, from `e - error = x - solution - error = x - solution*` (where `solution*` denotes the value stored in `solution` after the update) and `e = inv(A) residual = inv(A)b - inv(A) A solution = x - solution` it follows that | x - solution* | <= c | x - solution |.

Unless otherwise specified via the `solver` factory parameter, this implementation uses the identity operator (i.e. the solver that approximates the solution of a system Ax = b by setting x := b) as the default inner solver. Such a setting results in a relaxation method known as the Richardson iteration with parameter 1, which is guaranteed to converge for matrices whose spectrum is strictly contained within the unit disc around 1 (i.e., all its eigenvalues `lambda` have to satisfy the equation `|relaxation_factor * lambda - 1| < 1).

Template Parameters

ValueType	precision of matrix elements

32.63.2 Member Function Documentation

32.63.2.1 apply_uses_initial_guess()

```
template<typename ValueType = default_precision>
bool gko::solver::Ir< 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; }
```

32.63.2.2 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.

32.63.2.3 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

32.63.2.4 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

32.63.2.5 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)

32.63.2.6 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

new_solver	the new inner solver

32.63.2.7 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

other	the new stopping criterion factory

32.63.2.8 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

32.64 gko::preconditioner::Isai< 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.

32.64.1 Detailed Description

template<isai_type IsaiType, typename ValueType, typename IndexType>
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.

Using the preconditioner computes $aiU * x$ or $aiL * x$ (depending on the type of the Isai) 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

IsaiType	determines if the ISAI is generated for a lower triangular matrix or an upper triangular matrix
ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.64.2 Member Function Documentation

32.64.2.1 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.

32.64.2.2 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

32.64.2.3 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

32.65 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>
```

32.65.1 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

32.66 gko::log::iteration_complete_data Struct Reference

Struct representing iteration complete related data.

`#include <ginkgo/core/log/record.hpp>`

32.66.1 Detailed Description

Struct representing iteration complete related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.67 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.

32.67.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::preconditioner::Jacobi< ValueType, IndexType >

A block-Jacobi preconditioner is a block-diagonal linear operator, obtained by inverting the diagonal blocks of the source operator.

The Jacobi class implements the inversion of the diagonal blocks using Gauss-Jordan elimination with column pivoting, and stores the inverse explicitly in a customized format.

If the diagonal blocks of the matrix are not explicitly set by the user, the implementation will try to automatically detect the blocks by first finding the natural blocks of the matrix, and then applying the supervariable agglomeration procedure on them. However, if problem-specific knowledge regarding the block diagonal structure is available, it is usually beneficial to explicitly pass the starting rows of the diagonal blocks, as the block detection is merely a heuristic and cannot perfectly detect the diagonal block structure. The current implementation supports blocks of up to 32 rows / columns.

The implementation also includes an improved, adaptive version of the block-Jacobi preconditioner, which can store some of the blocks in lower precision and thus improve the performance of preconditioner application by reducing the amount of memory transfers. This variant can be enabled by setting the Jacobi::Factory's `storage_optimization` parameter. Refer to the documentation of the parameter for more details.

Template Parameters

ValueType	precision of matrix elements
IndexType	integral type used to store pointers to the start of each block

Note

The current implementation supports blocks of up to 32 rows / columns.

When using the adaptive variant, there may be a trade-off in terms of slightly longer preconditioner generation due to extra work required to detect the optimal precision of the blocks.

32.67.2 Member Function Documentation

32.67.2.1 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.

32.67.2.2 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

result	the object used to store the result of the conversion

Implements gko::ConvertibleTo< matrix::Dense< ValueType > >.

32.67.2.3 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().

32.67.2.4 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().

32.67.2.5 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

32.67.2.6 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().

32.67.2.7 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

32.67.2.8 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

result	the object used to emplace the result of the conversion

Note

ConvertibleTo::move_to can be implemented by simply calling ConvertibleTo::convert_to. However, this operation can often be optimized by exploiting the fact that implementer's data can be moved to the result.

Implements gko::ConvertibleTo< matrix::Dense< ValueType > >.

32.67.2.9 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.

32.67.2.10 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

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following file:

- ginkgo/core/preconditioner/jacobi.hpp

32.68 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.

32.68.1 Detailed Description

KernelNotFound is thrown if Ginkgo cannot find a kernel which satisfies the criteria imposed by the input arguments.

32.68.2 Constructor & Destructor Documentation

32.68.2.1 KernelNotFound()

```
gko::KernelNotFound::KernelNotFound (
            const std::string & file,
            int line,
            const std::string & func )  [inline]
```

Initializes a KernelNotFound error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function where the error occurred

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.69 gko::log::linop_data Struct Reference

Struct representing LinOp related data.

`#include <ginkgo/core/log/record.hpp>`

32.69.1 Detailed Description

Struct representing LinOp related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.70 gko::log::linop_factory_data Struct Reference

Struct representing LinOp factory related data.

`#include <ginkgo/core/log/record.hpp>`

32.70.1 Detailed Description

Struct representing LinOp factory related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.71 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

32.71.1 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)

32.71.1.1 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

32.72 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.

32.72.1 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.

32.72.2 Constructor & Destructor Documentation

32.72.2.1 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

exec	the CUDA executor

32.72.2.2 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

exec	the HIP executor

32.72.2.3 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

nwarps	the number of warps in the executor
warp_size	the warp size of the executor
cuda_strategy	whether the `cuda_strategy` 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.

32.72.3 Member Function Documentation

32.72.3.1 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

nnz	the number of nonzeros

Returns

the size of srow

Implements gko::matrix::Csr< ValueType, IndexType >::strategy_type.

References gko::ceildiv(), and gko::min().

32.72.3.2 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.

32.72.3.3 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.73 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.

32.73.1 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.

32.73.2 Member Function Documentation

32.73.2.1 add_logger()

```
virtual void gko::log::Loggable::add_logger (
            std::shared_ptr< const Logger > logger )  [pure virtual]
```

Adds a new logger to the list of subscribed loggers.

Parameters

logger	the logger to add

Implemented in gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >, gko::log::EnableLogging< PolymorphicObject >, and gko::log::EnableLogging< Executor >.

32.73.2.2 remove_logger()

```
virtual void gko::log::Loggable::remove_logger (
            const Logger * logger )  [pure virtual]
```

Removes a logger from the list of subscribed loggers.

Parameters

logger	the logger to remove

Note

The comparison is done using the logger's object unique identity. Thus, two loggers constructed in the same way are not considered equal.

Implemented in gko::log::EnableLogging< ConcreteLoggable, PolymorphicBase >, gko::log::EnableLogging< PolymorphicObject >, and gko::log::EnableLogging< Executor >.

The documentation for this class was generated from the following file:

- ginkgo/core/log/logger.hpp

32.74 gko::log::Record::logged_data Struct Reference

Struct storing the actually logged data.

```
#include <ginkgo/core/log/record.hpp>
```

32.74.1 Detailed Description

Struct storing the actually logged data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.75 gko::solver::LowerTrs< ValueType, IndexType > Class Template Reference

LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.

`#include <ginkgo/core/solver/lower_trs.hpp>`

Public Member Functions

- std::shared_ptr< const matrix::Csr< ValueType, IndexType > > get_system_matrix () const

  Gets the system operator (CSR matrix) of the linear system.
- std::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.

32.75.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::solver::LowerTrs< ValueType, IndexType >

LowerTrs is the triangular solver which solves the system L x = b, when L is a lower triangular matrix.

It works best when passing in a matrix in CSR format. If the matrix is not in CSR, then the generate step converts it into a CSR matrix. The generation fails if the matrix is not convertible to CSR.

Note

As the constructor uses the copy and convert functionality, it is not possible to create a empty solver or a solver with a matrix in any other format other than CSR, if none of the executor modules are being compiled with.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indices

32.75.2 Member Function Documentation

32.75.2.1 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.

32.75.2.2 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     }
```

32.75.2.3 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

32.76 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.

32.76.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
struct gko::matrix_data< ValueType, IndexType >

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

The matrix is stored as a sequence of nonzero elements, where each element is a triple of the form (row_index, column_index, value).

Note

All Ginkgo functions returning such a structure will return the nonzeros sorted in row-major order.

All Ginkgo functions that take this structure as input expect that the nonzeros are sorted in row-major order.

This structure is not optimized for usual access patterns and it can only exist on the CPU. Thus, it should only be used for utility functions which do not have to be optimized for performance.

Template Parameters

ValueType	type of matrix values stored in the structure
IndexType	type of matrix indexes stored in the structure

32.76.2 Constructor & Destructor Documentation

32.76.2.1 matrix_data() [1/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_ = dim<2>{},
            ValueType value = zero<ValueType>() )  [inline]
```

Initializes a matrix filled with the specified value.

Parameters

*size_*	dimensions of the matrix
value	value used to fill the elements of the matrix

```
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     }
```

32.76.2.2 matrix_data() [2/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename RandomDistribution , typename RandomEngine >
gko::matrix_data< ValueType, IndexType >::matrix_data (
             dim< 2 > size_,
             RandomDistribution && dist,
             RandomEngine && engine )  [inline]
```

Initializes a matrix with random values from the specified distribution.

Template Parameters

RandomDistribution	random distribution type
RandomEngine	random engine type

Parameters

size↩ _	dimensions of the matrix
dist	random distribution of the elements of the matrix
engine	random engine used to generate random values

32.76.2.3 matrix_data() [3/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
             std::initializer_list< std::initializer_list< ValueType >> values )  [inline]
```

List-initializes the structure from a matrix of values.

Parameters

values	a 2D braced-init-list of matrix values.

32.76.2.4 matrix_data() [4/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_,
            std::initializer_list< detail::input_triple< ValueType, IndexType >> nonzeros_ )
[inline]
```

Initializes the structure from a list of nonzeros.

Parameters

*size_*	dimensions of the matrix
*nonzeros_*	list of nonzero elements

32.76.2.5 matrix_data() [5/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
gko::matrix_data< ValueType, IndexType >::matrix_data (
            dim< 2 > size_,
            const matrix_data< ValueType, IndexType > & block )  [inline]
```

Initializes a matrix out of a matrix block via duplication.

Parameters

size	size of the block-matrix (in blocks)
diag_block	matrix block used to fill the complete matrix

References gko::matrix_data< ValueType, IndexType >::size.

32.76.2.6 matrix_data() [6/6]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename Accessor >
gko::matrix_data< ValueType, IndexType >::matrix_data (
            const range< Accessor > & data )  [inline]
```

Initializes a matrix from a range.

Template Parameters

Accessor	accessor type of the input range

Parameters

data	range used to initialize the matrix

References gko::range< Accessor >::length().

32.76.3 Member Function Documentation

32.76.3.1 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 Hausholder reflectors to a diagonal matrix with diagonal entries uniformly distributed between `sqrt(condition_number)` and `1/sqrt(condition_number)`.

This version of the function applies `size - 1` reflectors to each side of the diagonal matrix.

Template Parameters

RandomDistribution	the type of the random distribution
RandomEngine	the type of the random engine

Parameters

size	number of rows and columns of the matrix
condition_number	condition number of the matrix
dist	random distribution used to generate reflectors
engine	random engine used to generate reflectors

Returns

the dense matrix with the specified condition number

References gko::matrix_data< ValueType, IndexType >::cond(), and gko::matrix_data< ValueType, IndexType >::size.

32.76.3.2 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

RandomDistribution	the type of the random distribution
RandomEngine	the type of the random engine

Parameters

size	number of rows and columns of the matrix
condition_number	condition number of the matrix
dist	random distribution used to generate reflectors
engine	random engine used to generate reflectors
num_reflectors	number of reflectors to apply from each side

Returns

the dense matrix with the specified condition number

References gko::matrix_data< ValueType, IndexType >::size.

Referenced by gko::matrix_data< ValueType, IndexType >::cond().

32.76.3.3 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

*size_*	the size of the matrix
diag_block	matrix used to fill diagonal blocks

Returns

the block-diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros, and gko::matrix_data< ValueType, IndexType >::size.

32.76.3.4 diag() [2/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            dim< 2 > size_,
            std::initializer_list< ValueType > nonzeros_ )  [inline], [static]
```

Initializes a diagonal matrix using a list of diagonal elements.

Parameters

*size_*	dimensions of the matrix
*nonzeros_*	list of diagonal elements

Returns

the diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros.

32.76.3.5 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

*size_*	dimensions of the matrix
value	value used to fill the elements of the matrix

Returns

the diagonal matrix

References gko::matrix_data< ValueType, IndexType >::nonzeros.

Referenced by gko::matrix_data< ValueType, IndexType >::diag().

32.76.3.6 diag() [4/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
template<typename ForwardIterator >
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            ForwardIterator begin,
            ForwardIterator end )  [inline], [static]
```

Initializes a block-diagonal matrix from a list of diagonal blocks.

Template Parameters

ForwardIterator	type of list iterator

Parameters

begin	the first iterator of the list
end	the last iterator of the list

Returns

the block-diagonal matrix with diagonal blocks set to the blocks between begin (inclusive) and end (exclusive)

References gko::matrix_data< ValueType, IndexType >::nonzeros.

32.76.3.7 diag() [5/5]

```
template<typename ValueType = default_precision, typename IndexType = int32>
static matrix_data gko::matrix_data< ValueType, IndexType >::diag (
            std::initializer_list< matrix_data< ValueType, IndexType > > blocks )  [inline],
[static]
```

Initializes a block-diagonal matrix from a list of diagonal blocks.

Parameters

blocks	a list of blocks to initialize from

Returns

the block-diagonal matrix with diagonal blocks set to the blocks passed in blocks

References gko::matrix_data< ValueType, IndexType >::diag().

32.76.4 Member Data Documentation

32.76.4.1 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

32.77 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.

32.77.1 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

32.77.2 Member Function Documentation

32.77.2.1 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

nnz	the number of nonzeros

Returns

the size of srow

Implements gko::matrix::Csr< ValueType, IndexType >::strategy_type.

32.77.2.2 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.

32.77.2.3 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.78 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.

32.78.1 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.

32.78.2 Member Function Documentation

32.78.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
size_type gko::matrix::Hybrid< ValueType, IndexType >::minimal_storage_limit::compute_ell_↩
num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [inline], [override], [virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implements gko::matrix::Hybrid< ValueType, IndexType >::strategy_type.

References gko::matrix::Hybrid< ValueType, IndexType >::imbalance_limit::compute_ell_num_stored_elements_per_row().

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/hybrid.hpp

32.79 gko::matrix_data< ValueType, IndexType >::nonzero_type Struct Reference

Type used to store nonzeros.

`#include <ginkgo/core/base/matrix_data.hpp>`

32.79.1 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

32.80 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.

32.80.1 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.

32.80.2 Constructor & Destructor Documentation

32.80.2.1 NotCompiled()

```
gko::NotCompiled::NotCompiled (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & module )  [inline]
```

Initializes a NotCompiled error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function that has not been compiled
module	The name of the module which contains the function

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.81 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.

32.81.1 Detailed Description

NotImplemented is thrown in case an operation has not yet been implemented (but will be implemented in the future).

32.81.2 Constructor & Destructor Documentation

32.81.2.1 NotImplemented()

```
gko::NotImplemented::NotImplemented (
            const std::string & file,
            int line,
            const std::string & func )  [inline]
```

Initializes a NotImplemented error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the not-yet implemented function

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.82 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.

32.82.1 Detailed Description

NotSupported is thrown in case it is not possible to perform the requested operation on the given object type.

32.82.2 Constructor & Destructor Documentation

32.82.2.1 NotSupported()

```
gko::NotSupported::NotSupported (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & obj_type )  [inline]
```

Initializes a NotSupported error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function where the error occured
obj_type	The object type on which the requested operation cannot be performed.

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.83 gko::null_deleter< T > Class Template Reference

This is a deleter that does not delete the object.

`#include <ginkgo/core/base/utils.hpp>`

Public Member Functions

- void operator() (pointer) const noexcept
  Deletes the object.

32.83.1 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.

32.83.2 Member Function Documentation

32.83.2.1 operator()()

```
template<typename T >
void gko::null_deleter< T >::operator() (
            pointer  ) const  [inline], [noexcept]
```

Deletes the object.

Parameters

ptr	pointer to the object being deleted

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp

32.84 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.

32.84.1 Detailed Description

This is the Executor subclass which represents the OpenMP device (typically CPU).

32.84.2 Member Function Documentation

32.84.2.1 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.

32.84.2.2 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

32.85 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.

32.85.1 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() « ")"; }
    // 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::ReferenceExecutor::create() « std::endl;
```

which produces the expected output:

```
OMP
CUDA(0)
HIP(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, and the last one for HIP 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()
                   « ")"; });
    return os;
}
```

Using this approach, however, it is impossible to distinguish between a OmpExecutor and ReferenceExecutor, as both of them call the OMP closure.

32.85.2 Member Function Documentation

32.85.2.1 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

32.86 gko::log::operation_data Struct Reference

Struct representing Operator related data.

`#include <ginkgo/core/log/record.hpp>`

32.86.1 Detailed Description

Struct representing Operator related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.87 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.

32.87.1 Detailed Description

OutOfBoundsError is thrown if a memory access is detected to be out-of-bounds.

32.87.2 Constructor & Destructor Documentation

32.87.2.1 OutOfBoundsError()

```
gko::OutOfBoundsError::OutOfBoundsError (
            const std::string & file,
            int line,
            size_type index,
            size_type bound )  [inline]
```

Initializes an OutOfBoundsError.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
index	The position that was accessed
bound	The first out-of-bound index

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.88 gko::factorization::ParIct< ValueType, IndexType > Class Template Reference

ParICT is an incomplete threshold-based Cholesky factorization which is computed in parallel.

`#include <ginkgo/core/factorization/par_ict.hpp>`

Additional Inherited Members

32.88.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::ParIct< ValueType, IndexType >

ParICT 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 ParICT 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 ParICT algorithm thus improves the sparsity pattern and the approximation of L simultaneously.

The implementation follows the design of H. Anzt et al., ParILUT - A Parallel Threshold ILU for GPUs, 2019 IEEE International Parallel and Distributed Processing Symposium (IPDPS), pp. 231–241.

Template Parameters

ValueType	Type of the values of all matrices used in this class
IndexType	Type of the indices of all matrices used in this class

The documentation for this class was generated from the following file:

- ginkgo/core/factorization/par_ict.hpp

32.89 gko::factorization::ParIlu< ValueType, IndexType > Class Template Reference

ParILU is an incomplete LU factorization which is computed in parallel.

`#include <ginkgo/core/factorization/par_ilu.hpp>`

Additional Inherited Members

32.89.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::ParIlu< ValueType, IndexType >

ParILU is an incomplete LU factorization which is computed in parallel.

L is a lower unitriangular, while U is an upper triangular matrix, which approximate a given matrix A with $A \approx LU$. Here, L and U have the same sparsity pattern as A, which is also called ILU(0).

The ParILU algorithm generates the incomplete factors iteratively, using a fixed-point iteration of the form

$$F(L,U) = \begin{cases} \frac{1}{u_{jj}} \left(a_{ij} - \sum_{k=1}^{j-1} l_{ik} u_{kj} \right), & i > j \\ a_{ij} - \sum_{k=1}^{i-1} l_{ik} u_{kj}, & i \leq j \end{cases}$$

In general, the entries of L and U can be iterated in parallel and in asynchronous fashion, the algorithm asymptotically converges to the incomplete factors L and U fulfilling $(R = A - L \cdot U)\,|_{\mathcal{S}} = 0|_{\mathcal{S}}$ 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, 3 sweeps are typically generating a good approximation.

The ParILU algorithm in Ginkgo follows the design of E. Chow and A. Patel, Fine-grained Parallel Incomplete LU Factorization, SIAM Journal on Scientific Computing, 37, C169-C193 (2015).

Template Parameters

ValueType	Type of the values of all matrices used in this class
IndexType	Type of the indices of all matrices used in this class

The documentation for this class was generated from the following file:

- ginkgo/core/factorization/par_ilu.hpp

32.90 gko::factorization::ParIlut< ValueType, IndexType > Class Template Reference

ParILUT is an incomplete threshold-based LU factorization which is computed in parallel.

`#include <ginkgo/core/factorization/par_ilut.hpp>`

Additional Inherited Members

32.90.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::factorization::ParIlut< ValueType, IndexType >

ParILUT 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 ParILUT 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 ParILUT algorithm thus improves the sparsity pattern and the approximation of L and U simultaneously.

The implementation follows the design of H. Anzt et al., ParILUT - A Parallel Threshold ILU for GPUs, 2019 IEEE International Parallel and Distributed Processing Symposium (IPDPS), pp. 231–241.

Template Parameters

ValueType	Type of the values of all matrices used in this class
IndexType	Type of the indices of all matrices used in this class

The documentation for this class was generated from the following file:

- ginkgo/core/factorization/par_ilut.hpp

32.91 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 > 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 > *inverse_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 > *inverse_permutation_indices) const =0

  Returns a LinOp representing the row permutation of the inverse permuted object.

32.91.1 Detailed Description

template<typename IndexType>
class gko::Permutable< IndexType >

Linear operators which support permutation should implement the Permutable interface.

It provides four functionalities, the row permute, the column permute, the inverse row permute and the inverse column permute.

The row permute returns the permutation of the linear operator after permuting the rows of the linear operator. For example, if for a matrix A, the permuted matrix A' and the permutation array perm, the row i of the matrix A is the row perm[i] in the matrix A'. And similarly, for the inverse permutation, the row i in the matrix A' is the row perm[i] in the matrix A.

The column permute returns the permutation of the linear operator after permuting the columns of the linear operator. The definitions of permute and inverse permute for the row_permute hold here as well.

32.91.1.1 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);
```

32.91.2 Member Function Documentation

32.91.2.1 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.

Parameters

permutation_indices	the array of indices contaning the permutation order.

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 >

32.91.2.2 inverse_column_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::inverse_column_permute (
            const Array< IndexType > * inverse_permutation_indices ) const  [pure virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

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 >

32.91.2.3 inverse_row_permute()

```
template<typename IndexType>
virtual std::unique_ptr<LinOp> gko::Permutable< IndexType >::inverse_row_permute (
            const Array< IndexType > * inverse_permutation_indices ) const  [pure virtual]
```

Returns a LinOp representing the row permutation of the inverse permuted object.

Parameters

inverse_permutation_indices	the array of indices contaning the inverse permutation order.

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 >

32.91.2.4 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.

Parameters

permutation_indices	the array of indices contaning 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

32.92 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.

32.92.1 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

IndexType	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.

32.92.2 Member Function Documentation

32.92.2.1 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().

32.92.2.2 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().

32.92.2.3 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().

32.92.2.4 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

32.92.2.5 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

permute_mask	the permute masks

The documentation for this class was generated from the following file:

- ginkgo/core/matrix/permutation.hpp

32.93 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.

32.93.1 Detailed Description

template<typename ValueType = default_precision>
class gko::Perturbation< ValueType >

The Perturbation class can be used to construct a LinOp to represent the operation `(identity + scalar * basis * projector)`.

This operator adds a movement along a direction constructed by `basis` and `projector` on the LinOp. `projector` gives the coefficient of `basis` to decide the direction.

For example, the Householder matrix can be represented with the Perturbation operator as follows. If u is the Householder factor then we can generate the `Householder transformation`, H = (I - 2 u u∗). In this case, the parameters of Perturbation class are scalar = -2, basis = u, and projector = u∗.

Template Parameters

ValueType	precision of input and result vectors

Note

the apply operations of Perturbation class are not thread safe

32.93.2 Member Function Documentation

32.93.2.1 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     }
```

32.93.2.2 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

32.93.2.3 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

32.94 gko::log::polymorphic_object_data Struct Reference

Struct representing PolymorphicObject related data.

`#include <ginkgo/core/log/record.hpp>`

32.94.1 Detailed Description

Struct representing PolymorphicObject related data.

The documentation for this struct was generated from the following file:

- ginkgo/core/log/record.hpp

32.95 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.

32.95.1 Detailed Description

A PolymorphicObject is the abstract base for all "heavy" objects in Ginkgo that behave polymorphically.

It defines the basic utilities (copying moving, cloning, clearing the objects) for all such objects. It takes into account that these objects are dynamically allocated, managed by smart pointers, and used polymorphically. Additionally, it assumes their data can be allocated on different executors, and that they can be copied between those executors.

Note

Most of the public methods of this class should not be overridden directly, and are thus not virtual. Instead, there are equivalent protected methods (ending in <method_name>_impl) that should be overriden instead. This allows polymorphic objects to implement default behavior around virtual methods (parameter checking, type casting).

See also

EnablePolymorphicObject if you wish to implement a concrete polymorphic object and have sensible defaults generated automatically. EnableAbstractPolymorphicObject if you wish to implement a new abstract polymorphic object, and have the return types of the methods updated to your type (instead of having them return PolymorphicObject).

32.95.2 Member Function Documentation

32.95.2.1 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

32.95.2.2 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.

32.95.2.3 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

exec	the executor where the clone will be created

Returns

A clone of the LinOp.

References create_default().

32.95.2.4 copy_from() [1/2]

```
PolymorphicObject* gko::PolymorphicObject::copy_from (
            const PolymorphicObject * other )  [inline]
```

Copies another object into this object.

This is the polymorphic equivalent of the copy assignment operator.

See also

copy_from_impl(const PolymorphicObject *)

Parameters

other	the object to copy

Returns

this

32.95.2.5 copy_from() [2/2]

```
PolymorphicObject* gko::PolymorphicObject::copy_from (
            std::unique_ptr< PolymorphicObject > other )  [inline]
```

Moves another object into this object.

This is the polymorphic equivalent of the move assignment operator.

See also

copy_from_impl(std::unique_ptr<PolymorphicObject>)

Parameters

other	the object to move from

Returns

this

32.95.2.6 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().

32.95.2.7 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

exec	the executor where the object will be created

Returns

a polymorphic object of the same type as this

32.95.2.8 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::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::conj_transpose(), gko::matrix::Dense< ValueType >::create_submatrix(), gko::matrix::Dense< ValueType >::scale(), and gko::preconditioner::Ilu< LSolverType, USolverType, ReverseApply, IndexType >::transpose().

The documentation for this class was generated from the following file:

- ginkgo/core/base/polymorphic_object.hpp

32.96 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.

32.96.1 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.

32.96.2 Constructor & Destructor Documentation

32.96.2.1 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().

32.96.2.2 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

preserving	the number of range preserving conversion
nonpreserving	the number of range non-preserving conversions

32.96.3 Member Function Documentation

32.96.3.1 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.

32.96.3.2 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

x	an encoding
y	an encoding

Returns

the common encoding of `x` and `y`

References precision_reduction().

32.96.3.3 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.

32.96.3.4 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.

32.96.3.5 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

32.97 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.

32.97.1 Detailed Description

A LinOp implementing this interface can be preconditioned.

32.97.2 Member Function Documentation

32.97.2.1 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

```
582     {
583         return preconditioner_;
584     }
```

32.97.2.2 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

new_precond	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

32.98 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.

32.98.1 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.

32.98.1.1 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.

32.98.1.2 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` an `y` are ranges, and `alpha` is a scalar. Range operations are optimized for memory access, and the above code does not allocate additional storage for intermediate ranges `alpha * x` or `aplha * x + y`. In fact, the entire computation is done during the assignment, and the results of operations + and ∗ only register the data, and the types of operations that will be computed once the results are needed.

It is possible to store and reuse these intermediate expressions. The following example will overwrite the range `x` with it's 4th power:

```
 {c++}
auto square = x * x;  // this is range constructor, not range assignment!
x = square;  // overwrites x with x*x (this is range assignment)
x = square;  // overwrites new x (x*x) with (x*x)*(x*x) (as is this)
```

32.98.1.3 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-perfromance matrix multiplication, you should use one of the libraries that provide that, or implement your own (you can use pointwise range operations to help simplify that). However, range design might get improved in the future to allow efficient implementations of BLAS-3 kernels.

Aliasing the result range in `mmul` and `transpose` is not allowed. Constructs like `A = transpose(A)`, `A = mmul(A, A)`, or `A = mmul(A, A) + C` lead to undefined behavior. However, aliasing input arguments is allowed: `C = mmul(A, A)`, and even `C = mmul(A, A) + C` is valid code (in the last example, only pointwise operations are aliased). `C = mmul(A, A + C)` is not valid though.

32.98.1.4 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 `span`s as arguments to range function call operator. Finally, examples/range contains a complete example where ranges are used to implement a simple version of the right-looking LU factorization.

Template Parameters

Accessor	underlying accessor of the range

32.98.2 Constructor & Destructor Documentation

32.98.2.1 range()

```
template<typename Accessor>
template<typename...  AccessorParams>
constexpr gko::range< Accessor >::range (
            AccessorParams &&...  params )  [inline], [explicit], [constexpr]
```

Creates a new range.

Template Parameters

AccessorParam	types of parameters forwarded to the accessor constructor

Parameters

params	parameters forwarded to Accessor constructor.

```
325         : accessor_{std::forward<AccessorParams>(params)...}
326     {}
```

32.98.3 Member Function Documentation

32.98.3.1 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=().

32.98.3.2 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

dimension	the dimensions whose length is returned

Returns

the length of the `dimension`-th dimension of the range

Referenced by gko::matrix_data< ValueType, IndexType >::matrix_data().

32.98.3.3 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

DimensionTypes	The types of indexes. Supported types depend on the underlying accessor, but are usually either integer types or spans. If at least one index is a span, the returned value will be a sub-range.

Parameters

dimensions	the indexes of the values.

Returns

a value on position `(dimensions...)`.

References gko::range< Accessor >::dimensionality.

32.98.3.4 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

32.98.3.5 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

other	the range to copy the data from

References gko::range< Accessor >::get_accessor().

32.98.3.6 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

OtherAccessor	accessor of the other range

The documentation for this class was generated from the following file:

- ginkgo/core/base/range.hpp

32.99 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.

32.99.1 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.

32.99.2 Member Function Documentation

32.99.2.1 read()

```
template<typename ValueType, typename IndexType>
virtual void gko::ReadableFromMatrixData< ValueType, IndexType >::read (
            const matrix_data< ValueType, IndexType > & data )  [pure virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implemented in gko::matrix::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

32.100 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.

32.100.1 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.

32.100.2 Member Function Documentation

32.100.2.1 create()

```
static std::unique_ptr<Record> gko::log::Record::create (
            std::shared_ptr< const Executor > exec,
            const mask_type & enabled_events = Logger::all_events_mask,
            size_type max_storage = 1 )  [inline], [static]
```

Creates a Record logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.
max_storage	the size of storage (i.e. history) wanted by the user. By default 0 is used, which means unlimited storage. It is advised to control this to reduce memory overhead of this logger.

Returns

an std::unique_ptr to the the constructed object

```
395     {
396         return std::unique_ptr<Record>(
397             new Record(exec, enabled_events, max_storage));
398     }
```

32.100.2.2 get() [1/2]

```
const logged_data& gko::log::Record::get ( ) const  [inline], [noexcept]
```

Returns the logged data.

Returns

the logged data

32.100.2.3 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

32.101 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

32.101.1 Detailed Description

This is a specialization of the OmpExecutor, which runs the reference implementations of the kernels used for debugging purposes.

32.101.2 Member Function Documentation

32.101.2.1 run()

```
void gko::ReferenceExecutor::run (
            const Operation & op ) const  [inline], [override], [virtual]
```

Runs the specified Operation using this Executor.

Parameters

op	the operation to run

Implements gko::Executor.

The documentation for this class was generated from the following file:

- ginkgo/core/base/executor.hpp

32.102 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>`

32.102.1 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 norm(residual) / norm(right_hand_side) < 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

32.103 gko::stop::ResidualNorm< ValueType > Class Template Reference

The ResidualNorm class provides a framework for stopping criteria related to the residual norm.

`#include <ginkgo/core/stop/residual_norm.hpp>`

32.103.1 Detailed Description

template<typename ValueType = default_precision>
class gko::stop::ResidualNorm< ValueType >

The ResidualNorm 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 documentation for this class was generated from the following file:

- ginkgo/core/stop/residual_norm.hpp

32.104 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>`

32.104.1 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 norm(residual) / norm(initial_residual) < 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

32.105 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.

32.105.1 Detailed Description

template<typename ValueType, size_type Dimensionality>
class gko::accessor::row_major< ValueType, Dimensionality >

A row_major accessor is a bridge between a range and the row-major memory layout.

You should never try to explicitly create an instance of this accessor. Instead, supply it as a template parameter to a range, and pass the constructor parameters for this class to the range (it will forward it to this class).

Warning

The current implementation is incomplete, and only allows for 2-dimensional ranges.

Template Parameters

ValueType	type of values this accessor returns
Dimensionality	number of dimensions of this accessor (has to be 2)

32.105.2 Member Function Documentation

32.105.2.1 copy_from()

```
template<typename ValueType , size_type Dimensionality>
template<typename OtherAccessor >
void gko::accessor::row_major< ValueType, Dimensionality >::copy_from (
            const OtherAccessor & other ) const  [inline]
```

Copies data from another accessor.

Template Parameters

OtherAccessor	type of the other accessor

Parameters

other	other accessor

```
164     {
165         for (size_type i = 0; i < lengths[0]; ++i) {
166             for (size_type j = 0; j < lengths[1]; ++j) {
167                 (*this)(i, j) = other(i, j);
168             }
169         }
170     }
```

References gko::accessor::row_major< ValueType, Dimensionality >::lengths.

32.105.2.2 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

dimension	a dimension index

Returns

length in dimension `dimension`

References gko::accessor::row_major< ValueType, Dimensionality >::lengths.

32.105.2.3 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

rows	row span
cols	column span

Returns

sub-range spanning the range (rows, cols)

References gko::span::begin, gko::accessor::row_major< ValueType, Dimensionality >::data, gko::span::end, gko::span::is_valid(), gko::accessor::row_major< ValueType, Dimensionality >::lengths, and gko::accessor::row_major< ValueType, Dimensionality >::stride.

32.105.2.4 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

row	row index
col	column index

Returns

data element at (row, col)

References gko::accessor::row_major< ValueType, Dimensionality >::data, gko::accessor::row_major< ValueType, Dimensionality >::lengths, and gko::accessor::row_major< ValueType, Dimensionality >::stride.

The documentation for this class was generated from the following file:

- ginkgo/core/base/range_accessors.hpp

32.106 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.
- 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.

32.106.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::matrix::Sellp< ValueType, IndexType >

SELL-P is a matrix format similar to ELL format.

The difference is that SELL-P format divides rows into smaller slices and store each slice with ELL format.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indexes

32.106.2 Member Function Documentation

32.106.2.1 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

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

```
271     {
272         return this
273             ->get_const_col_idxs()[this->linearize_index(row, slice_set, idx)];
274     }
```

32.106.2.2 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

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs().

32.106.2.3 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

diag	the vector into which the diagonal will be written

Implements gko::DiagonalExtractable< ValueType >.

32.106.2.4 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::Sellp< ValueType, IndexType >::get_col_idxs ( ) [inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

References gko::Array< ValueType >::get_data().

Referenced by gko::matrix::Sellp< ValueType, IndexType >::col_at().

32.106.2.5 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_col_idxs ( ) const
[inline], [noexcept]
```

Returns the column indexes of the matrix.

Returns

the column indexes of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

32.106.2.6 get_const_slice_lengths()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_lengths ( ) const
[inline], [noexcept]
```

Returns the lengths(columns) of slices.

Returns

the lengths(columns) of slices.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

32.106.2.7 get_const_slice_sets()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const size_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_slice_sets ( ) const
[inline], [noexcept]
```

Returns the offsets of slices.

Returns

the offsets of slices.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

32.106.2.8 get_const_values()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const value_type* gko::matrix::Sellp< ValueType, IndexType >::get_const_values ( ) const  [inline],
[noexcept]
```

Returns the values of the matrix.

Returns

the values of the matrix.

Note

This is the constant version of the function, which can be significantly more memory efficient than the non-constant version, so always prefer this version.

References gko::Array< ValueType >::get_const_data().

32.106.2.9 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().

32.106.2.10 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().

32.106.2.11 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().

32.106.2.12 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.

32.106.2.13 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.

32.106.2.14 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.

32.106.2.15 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().

32.106.2.16 read()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Sellp< ValueType, IndexType >::read (
            const mat_data & data )  [override], [virtual]
```

Reads a matrix from a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.106.2.17 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

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::Array< ValueType >::get_const_data().

32.106.2.18 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

row	the row of the requested element in the slice
slice_set	the slice set of the slice
idx	the idx-th stored element of the row in the slice

Note

the method has to be called on the same Executor the matrix is stored at (e.g. trying to call this method on a GPU matrix from the CPU results in a runtime error)

References gko::Array< ValueType >::get_data().

32.106.2.19 write()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Sellp< ValueType, IndexType >::write (
             mat_data & data ) const  [override], [virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp
- ginkgo/core/matrix/sellp.hpp

32.107 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.

32.107.1 Detailed Description

A span is a lightweight structure used to create sub-ranges from other ranges.

A `span s` represents a contiguous set of indexes in one dimension of the range, starting on index `s.begin` (inclusive) and ending at index `s.end` (exclusive). A span is only valid if its starting index is smaller than its ending index.

Spans can be compared using the `==` and `!=` operators. Two spans are identical if both their `begin` and `end` values are identical.

Spans also have two distinct partial orders defined on them:

1. `x < y` (`y > x`) if and only if `x.end < y.begin`
2. `x <= y` (`y >= x`) if and only if `x.end <= y.begin`

Note that the orders are in fact partial - there are spans `x` and `y` for which none of the following inequalities holds: `x < y`, `x > y`, `x == y`, `x <= y`, `x >= y`. An example are spans `span{0, 2}` and `span{1, 3}`.

In addition, `<=` is a distinct order from `<`, and not just an extension of the strict order to its weak equivalent. Thus, `x <= y` is not equivalent to `x < y || x == y`.

32.107.2 Constructor & Destructor Documentation

32.107.2.1 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

point	the point which the span represents

32.107.2.2 span() [2/2]

```
constexpr gko::span::span (
            size_type begin,
            size_type end )  [inline], [constexpr], [noexcept]
```

Creates a span.

Parameters

begin	the beginning of the span
end	the end of the span

References begin.

32.107.3 Member Function Documentation

32.107.3.1 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

32.108 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.

32.108.1 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.

32.108.2 Member Function Documentation

32.108.2.1 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

nnz	the number of nonzeros

Returns

the size of srow

Implements gko::matrix::Csr< ValueType, IndexType >::strategy_type.

32.108.2.2 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.

32.108.2.3 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.109 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.

32.109.1 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

ValueType	precision of vectors in apply
IndexType	precision of matrix indexes

32.109.2 Member Function Documentation

32.109.2.1 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.

32.109.2.2 get_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
index_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_col_idxs ( )  [inline],
[noexcept]
```

Returns the column indices of the matrix.

Returns

the column indices of the matrix.

```
126 { return col_idxs_.get_data(); }
```

References gko::Array< ValueType >::get_data().

32.109.2.3 get_const_col_idxs()

```
template<typename ValueType = default_precision, typename IndexType = int32>
const index_type* gko::matrix::SparsityCsr< ValueType, IndexType >::get_const_col_idxs ( )
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().

32.109.2.4 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().

32.109.2.5 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().

32.109.2.6 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().

32.109.2.7 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().

32.109.2.8 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().

32.109.2.9 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

data	the matrix_data structure

Implements gko::ReadableFromMatrixData< ValueType, IndexType >.

32.109.2.10 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.

32.109.2.11 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.

32.109.2.12 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

data	the matrix_data structure

Implements gko::WritableToMatrixData< ValueType, IndexType >.

The documentation for this class was generated from the following files:

- ginkgo/core/matrix/csr.hpp
- ginkgo/core/matrix/sparsity_csr.hpp

32.110 gko::stopping_status Class Reference

This class is used to keep track of the stopping status of one vector.

`#include <ginkgo/core/stop/stopping_status.hpp>`

Public Member Functions

- bool has_stopped () const noexcept

  Check if any stopping criteria was fulfilled.
- bool has_converged () const noexcept

  Check if convergence was reached.
- bool is_finalized () const noexcept

  Check if the corresponding vector stores the finalized result.
- uint8 get_id () const noexcept

  Get the id of the stopping criterion which caused the stop.
- void reset () noexcept

  Clear all flags.
- void stop (uint8 id, bool set_finalized=true) noexcept

  Call if a stop occured due to a hard limit (and convergence was not reached).
- void converge (uint8 id, bool set_finalized=true) noexcept

  Call if convergence occured.
- void finalize () noexcept

  Set the result to be finalized (it needs to be stopped or converged first).

Friends

- bool operator== (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are equivalent.
- bool operator!= (const stopping_status &x, const stopping_status &y) noexcept

  Checks if two stopping statuses are different.

32.110.1 Detailed Description

This class is used to keep track of the stopping status of one vector.

32.110.2 Member Function Documentation

32.110.2.1 converge()

```
void gko::stopping_status::converge (
            uint8 id,
            bool set_finalized = true )  [inline], [noexcept]
```

Call if convergence occured.

Parameters

id	id of the stopping criteria.
set_finalized	Controls if the current version should count as finalized (set to true) or not (set to false).

References has_stopped().

32.110.2.2 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().

32.110.2.3 has_converged()

```
bool gko::stopping_status::has_converged ( ) const  [inline], [noexcept]
```

Check if convergence was reached.

Returns

Returns true if convergence was reached.

32.110.2.4 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().

32.110.2.5 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.

32.110.2.6 stop()

```
void gko::stopping_status::stop (
            uint8 id,
            bool set_finalized = true )  [inline], [noexcept]
```

Call if a stop occured due to a hard limit (and convergence was not reached).

Parameters

id	id of the stopping criteria.
set_finalized	Controls if the current version should count as finalized (set to true) or not (set to false).

References has_stopped().

32.110.3 Friends And Related Function Documentation

32.110.3.1 operator"!=

```
bool operator!= (
            const stopping_status & x,
            const stopping_status & y )  [friend]
```

Checks if two stopping statuses are different.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if `!(x == y)`

32.110.3.2 operator==

```
bool operator== (
            const stopping_status & x,
            const stopping_status & y )  [friend]
```

Checks if two stopping statuses are equivalent.

Parameters

x	a stopping status
y	a stopping status

Returns

true if and only if both x and y have the same mask and converged and finalized state

The documentation for this class was generated from the following file:

- ginkgo/core/stop/stopping_status.hpp

32.111 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.

32.111.1 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.

32.111.2 Constructor & Destructor Documentation

32.111.2.1 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

name	the name of strategy

32.111.3 Member Function Documentation

32.111.3.1 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

nnz	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.

32.111.3.2 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.

32.111.3.3 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

32.111.3.4 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

mtx_row_ptrs	the row pointers of the matrix
mtx_srow	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

32.112 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.

32.112.1 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.

32.112.2 Member Function Documentation

32.112.2.1 compute_ell_num_stored_elements_per_row()

```
template<typename ValueType = default_precision, typename IndexType = int32>
virtual size_type gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_ell_num_stored_elements_per_row (
            Array< size_type > * row_nnz ) const  [pure virtual]
```

Computes the number of stored elements per row of the ell part.

Parameters

row_nnz	the number of nonzeros of each row

Returns

the number of stored elements per row of the ell part

Implemented in gko::matrix::Hybrid< ValueType, IndexType >::automatic, gko::matrix::Hybrid< ValueType, IndexType >::minimal_st
gko::matrix::Hybrid< ValueType, IndexType >::imbalance_bounded_limit, gko::matrix::Hybrid< ValueType, IndexType >::imbalance_
and gko::matrix::Hybrid< ValueType, IndexType >::column_limit.

Referenced by gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config().

32.112.2.2 compute_hybrid_config()

```
template<typename ValueType = default_precision, typename IndexType = int32>
void gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_hybrid_config (
            const Array< size_type > & row_nnz,
            size_type * ell_num_stored_elements_per_row,
            size_type * coo_nnz )  [inline]
```

Computes the config of the Hybrid matrix (ell_num_stored_elements_per_row and coo_nnz).

For now, it copies row_nnz to the reference executor and performs all operations on the reference executor.

Parameters

row_nnz	the number of nonzeros of each row
ell_num_stored_elements_per_row	the output number of stored elements per row of the ell part
coo_nnz	the output number of nonzeros of the coo part

References gko::matrix::Hybrid< ValueType, IndexType >::strategy_type::compute_ell_num_stored_elements_↩
per_row(), gko::Array< ValueType >::get_executor(), and gko::Array< ValueType >::get_num_elems().

32.112.2.3 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

32.112.2.4 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

32.113 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.

32.113.1 Detailed Description

template<typename ValueType = default_precision>
class gko::log::Stream< ValueType >

Stream is a Logger which logs every event to a stream.

This can typically be used to log to a file or to the console.

Template Parameters

ValueType	the type of values stored in the class (i.e. ValueType template parameter of the concrete Loggable this class will log)

32.113.2 Member Function Documentation

32.113.2.1 create()

```
template<typename ValueType = default_precision>
static std::unique_ptr<Stream> gko::log::Stream< ValueType >::create (
            std::shared_ptr< const Executor > exec,
            const Logger::mask_type & enabled_events = Logger::all_events_mask,
            std::ostream & os = std::cout,
            bool verbose = false )  [inline], [static]
```

Creates a Stream logger.

This dynamically allocates the memory, constructs the object and returns an std::unique_ptr to this object.

Parameters

exec	the executor
enabled_events	the events enabled for this logger. By default all events.
os	the stream used for this logger
verbose	whether we want detailed information or not. This includes always printing residuals and other information which can give a large output.

Returns

an std::unique_ptr to the the constructed object

```
178     {
179         return std::unique_ptr<Stream>(
180             new Stream(exec, enabled_events, os, verbose));
181     }
```

The documentation for this class was generated from the following file:

- ginkgo/core/log/stream.hpp

32.114 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.

32.114.1 Detailed Description

StreamError is thrown if accessing a stream failed.

32.114.2 Constructor & Destructor Documentation

32.114.2.1 StreamError()

```
gko::StreamError::StreamError (
            const std::string & file,
            int line,
            const std::string & func,
            const std::string & message )  [inline]
```

Initializes a file access error.

Parameters

file	The name of the offending source file
line	The source code line number where the error occurred
func	The name of the function that tried to access the file
message	The error message

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.115 gko::temporary_clone< T > Class Template Reference

A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.

`#include <ginkgo/core/base/utils.hpp>`

Public Member Functions

- temporary_clone (std::shared_ptr< const Executor > exec, pointer ptr)
  Creates a temporary_clone.
- T * get () const
  Returns the object held by temporary_clone.
- T * operator-> () const
  Calls a method on the underlying object.

32.115.1 Detailed Description

template<typename T>
class gko::temporary_clone< T >

A temporary_clone is a special smart pointer-like object that is designed to hold an object temporarily copied to another executor.

After the temporary_clone goes out of scope, the stored object will be copied back to its original location. This class is optimized to avoid copies if the object is already on the correct executor, in which case it will just hold a reference to that object, without performing the copy.

Template Parameters

T	the type of object held in the temporary_clone

32.115.2 Constructor & Destructor Documentation

32.115.2.1 temporary_clone()

```
template<typename T >
gko::temporary_clone< T >::temporary_clone (
            std::shared_ptr< const Executor > exec,
            pointer ptr )  [inline], [explicit]
```

Creates a temporary_clone.

Parameters

exec	the executor where the clone will be created
ptr	a pointer to the object of which the clone will be created

References gko::clone().

32.115.3 Member Function Documentation

32.115.3.1 get()

```
template<typename T >
T* gko::temporary_clone< T >::get ( ) const  [inline]
```

Returns the object held by temporary_clone.

Returns

the object held by temporary_clone

32.115.3.2 operator->()

```
template<typename T >
T* gko::temporary_clone< T >::operator-> ( ) const  [inline]
```

Calls a method on the underlying object.

Returns

the underlying object

The documentation for this class was generated from the following file:

- ginkgo/core/base/utils.hpp

32.116 gko::stop::Time Class Reference

The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

```
#include <ginkgo/core/stop/time.hpp>
```

32.116.1 Detailed Description

The Time class is a stopping criterion which stops the iteration process after a certain amout of time has passed.

The documentation for this class was generated from the following file:

- ginkgo/core/stop/time.hpp

32.117 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.

32.117.1 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, $B = A^H$.

32.117.1.1 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();
```

32.117.2 Member Function Documentation

32.117.2.1 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::Isai< IsaiType, ValueType, IndexType >, gko::solver::Ir< ValueType >, gko::solver::LowerTrs< ValueType, Index gko::solver::UpperTrs< ValueType, IndexType >, gko::solver::Fcg< ValueType >, gko::solver::Bicgstab< ValueType >, gko::matrix::SparsityCsr< ValueType, IndexType >, gko::solver::Cg< ValueType >, gko::solver::Gmres< ValueType >, gko::solver::Bicg< ValueType >, gko::matrix::Diagonal< ValueType >, gko::solver::Cgs< ValueType >, gko::Combination< ValueTyp gko::Composition< ValueType >, and gko::matrix::Identity< ValueType >.

32.117.2.2 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::Isai< IsaiType, ValueType, IndexType >, gko::solver::Ir< ValueType >, gko::solver::LowerTrs< ValueType, Index gko::solver::UpperTrs< ValueType, IndexType >, gko::solver::Fcg< ValueType >, gko::solver::Bicgstab< ValueType >, gko::matrix::SparsityCsr< ValueType, IndexType >, gko::solver::Cg< ValueType >, gko::solver::Gmres< ValueType >, gko::solver::Bicg< ValueType >, gko::matrix::Diagonal< ValueType >, gko::solver::Cgs< ValueType >, gko::Combination< ValueTyp 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

32.118 gko::stop::Criterion::Updater Class Reference

The Updater class serves for convenient argument passing to the Criterion's check function.

```
#include <ginkgo/core/stop/criterion.hpp>
```

Public Member Functions

- Updater (const Updater &)=delete

  Prevent copying and moving the object This is to enforce the use of argument passing and calling check at the same time.
- bool check (uint8 stoppingId, bool setFinalized, Array< stopping_status > *stop_status, bool *one_changed) const

  Calls the parent Criterion object's check method.

32.118.1 Detailed Description

The Updater class serves for convenient argument passing to the Criterion's check function.

The pattern used is a Builder, except Updater builds a function's arguments before calling the function itself, and does not build an object. This allows calling a Criterion's check in the form of: stop_criterion->update() .num_↩ iterations(num_iterations) .residual_norm(residual_norm) .residual(residual) .solution(solution) .check(converged);

If there is a need for a new form of data to pass to the Criterion, it should be added here.

32.118.2 Member Function Documentation

32.118.2.1 check()

```
bool gko::stop::Criterion::Updater::check (
            uint8 stoppingId,
            bool setFinalized,
            Array< stopping_status > * stop_status,
            bool * one_changed ) const  [inline]
```

Calls the parent Criterion object's check method.

References gko::stop::Criterion::check().

The documentation for this class was generated from the following file:

- ginkgo/core/stop/criterion.hpp

32.119 gko::solver::UpperTrs< ValueType, IndexType > Class Template Reference

UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

`#include <ginkgo/core/solver/upper_trs.hpp>`

Public Member Functions

- std::shared_ptr< const matrix::Csr< ValueType, IndexType > > get_system_matrix () const
  Gets the system operator (CSR matrix) of the linear system.
- std::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.

32.119.1 Detailed Description

template<typename ValueType = default_precision, typename IndexType = int32>
class gko::solver::UpperTrs< ValueType, IndexType >

UpperTrs is the triangular solver which solves the system U x = b, when U is an upper triangular matrix.

It works best when passing in a matrix in CSR format. If the matrix is not in CSR, then the generate step converts it into a CSR matrix. The generation fails if the matrix is not convertible to CSR.

Note

As the constructor uses the copy and convert functionality, it is not possible to create a empty solver or a solver with a matrix in any other format other than CSR, if none of the executor modules are being compiled with.

Template Parameters

ValueType	precision of matrix elements
IndexType	precision of matrix indices

32.119.2 Member Function Documentation

32.119.2.1 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.

32.119.2.2 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     }
```

32.119.2.3 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

32.120 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.

32.120.1 Detailed Description

ValueMismatch is thrown if two values are not equal.

32.120.2 Constructor & Destructor Documentation

32.120.2.1 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

file	The name of the offending source file
line	The source code line number where the error occurred
func	The function name where the error occurred
val1	The first value to be compared.
val2	The second value to be compared.
clarification	An additional message further describing the error

The documentation for this class was generated from the following file:

- ginkgo/core/base/exception.hpp

32.121 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.

32.121.1 Detailed Description

This structure is used to represent versions of various Ginkgo modules.

Version structures can be compared using the usual relational operators.

32.121.2 Member Data Documentation

32.121.2.1 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

32.122 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.

32.122.1 Detailed Description

Ginkgo uses version numbers to label new features and to communicate backward compatibility guarantees:

1. Versions with different major version number have incompatible interfaces (parts of the earlier interface may not be present anymore, and new interfaces can appear).
2. Versions with the same major number X, but different minor numbers Y1 and Y2 numbers keep the same interface as version X.0.0, but additions to the interface in X.0.0 present in X.Y1.0 may not be present in X.Y2.0 and vice versa.
3. Versions with the same major an minor version numbers, but different patch numbers have exactly the same interface, but the functionality may be different (something that is not implemented or has a bug in an earlier version may have this implemented or fixed in a later version).

This structure provides versions of different parts of Ginkgo: the headers, the core and the kernel modules (reference, OpenMP, CUDA, HIP). To obtain an instance of version_info filled with information about the current version of Ginkgo, call the version_info::get() static method.

32.122.2 Member Function Documentation

32.122.2.1 get()

```
static const version_info& gko::version_info::get ( )  [inline], [static]
```

Returns an instance of version_info.

Returns

an instance of version info

32.122.3 Member Data Documentation

32.122.3.1 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".

32.122.3.2 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".

32.122.3.3 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".

32.122.3.4 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".

32.122.3.5 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

32.123 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.

32.123.1 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.

32.123.2 Member Function Documentation

32.123.2.1 write()

```
template<typename ValueType, typename IndexType>
virtual void gko::WritableToMatrixData< ValueType, IndexType >::write (
            matrix_data< ValueType, IndexType > & data ) const  [pure virtual]
```

Writes a matrix to a matrix_data structure.

Parameters

data	the matrix_data structure

Implemented in gko::matrix::Csr< ValueType, IndexType >, gko::matrix::Hybrid< ValueType, IndexType >, gko::preconditioner::Jacobi< ValueType, IndexType >, gko::matrix::Coo< ValueType, IndexType >, gko::matrix::Ell< ValueType, Inde 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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