

Final Project

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0.1 Part 1

The cell below is for imports. You are only allowed to use `numpy` for this part. No additional imports are allowed

```
[2]: import os
arch = os.getenv("ARGS", "real")

try:
    import google.colab # noqa: F401
except ImportError:
    import petsc4py
else:
    try:
        import petsc4py
    except ImportError:
        if arch != "complex":
            !wget "https://fem-on-colab.github.io/releases/
↪petsc4py-install-real.sh" -O "/tmp/petsc4py-install.sh" && bash "/tmp/
↪petsc4py-install.sh"
        else:
            !wget "https://fem-on-colab.github.io/releases/
↪petsc4py-install-complex.sh" -O "/tmp/petsc4py-install.sh" && bash "/tmp/
↪petsc4py-install.sh"
```

```
import petsc4py
```

```
--2023-04-19 21:11:54-- https://fem-on-colab.github.io/releases/petsc4py-  
install-real.sh
```

```
Resolving fem-on-colab.github.io (fem-on-colab.github.io)... 185.199.108.153,  
185.199.109.153, 185.199.110.153, ...
```

```
Connecting to fem-on-colab.github.io (fem-on-  
colab.github.io)|185.199.108.153|:443... connected.
```

```
HTTP request sent, awaiting response... 200 OK
```

```
Length: 1793 (1.8K) [application/x-sh]
```

```
Saving to: '/tmp/petsc4py-install.sh'
```

```
/tmp/petsc4py-insta 100%[=====>] 1.75K --.-KB/s in 0s
```

```
2023-04-19 21:11:54 (19.0 MB/s) - '/tmp/petsc4py-install.sh' saved [1793/1793]
```

```
+ INSTALL_PREFIX=/usr/local  
++ echo /usr/local  
++ awk -F/ '{print NF-1}'  
+ INSTALL_PREFIX_DEPTH=2  
+ PROJECT_NAME=fem-on-colab  
+ SHARE_PREFIX=/usr/local/share/fem-on-colab  
+ PETSC4PY_INSTALLED=/usr/local/share/fem-on-colab/petsc4py.installed  
+ [[ ! -f /usr/local/share/fem-on-colab/petsc4py.installed ]]  
+ H5PY_INSTALL_SCRIPT_PATH=https://github.com/fem-on-colab/fem-on-  
colab.github.io/raw/9d19467/releases/h5py-install.sh  
+ [[ https://github.com/fem-on-colab/fem-on-  
colab.github.io/raw/9d19467/releases/h5py-install.sh == http* ]]  
+ H5PY_INSTALL_SCRIPT_DOWNLOAD=https://github.com/fem-on-colab/fem-on-  
colab.github.io/raw/9d19467/releases/h5py-install.sh  
+ H5PY_INSTALL_SCRIPT_PATH=/tmp/h5py-install.sh  
+ [[ ! -f /tmp/h5py-install.sh ]]  
+ source /tmp/h5py-install.sh  
++ set -e  
++ set -x  
++ INSTALL_PREFIX=/usr/local  
+++ echo /usr/local  
+++ awk -F/ '{print NF-1}'  
++ INSTALL_PREFIX_DEPTH=2  
++ PROJECT_NAME=fem-on-colab  
++ SHARE_PREFIX=/usr/local/share/fem-on-colab  
++ H5PY_INSTALLED=/usr/local/share/fem-on-colab/h5py.installed  
++ [[ ! -f /usr/local/share/fem-on-colab/h5py.installed ]]  
++ MPI4PY_INSTALL_SCRIPT_PATH=https://github.com/fem-on-colab/fem-on-  
colab.github.io/raw/1eca11b/releases/mpi4py-install.sh  
++ [[ https://github.com/fem-on-colab/fem-on-  
colab.github.io/raw/1eca11b/releases/mpi4py-install.sh == http* ]]  
++ MPI4PY_INSTALL_SCRIPT_DOWNLOAD=https://github.com/fem-on-colab/fem-on-
```

```

colab.github.io/raw/1eca11b/releases/mpi4py-install.sh
++ MPI4PY_INSTALL_SCRIPT_PATH=/tmp/mpi4py-install.sh
++ [[ ! -f /tmp/mpi4py-install.sh ]]
++ source /tmp/mpi4py-install.sh
+++ set -e
+++ set -x
+++ INSTALL_PREFIX=/usr/local
++++ echo /usr/local
++++ awk -F/ '{print NF-1}'
+++ INSTALL_PREFIX_DEPTH=2
+++ PROJECT_NAME=fem-on-colab
+++ SHARE_PREFIX=/usr/local/share/fem-on-colab
+++ MPI4PY_INSTALLED=/usr/local/share/fem-on-colab/mpi4py.installed
+++ [[ ! -f /usr/local/share/fem-on-colab/mpi4py.installed ]]
+++ GCC_INSTALL_SCRIPT_PATH=https://github.com/fem-on-colab/fem-on-
colab.github.io/raw/d975b3f/releases/gcc-install.sh
+++ [[ https://github.com/fem-on-colab/fem-on-
colab.github.io/raw/d975b3f/releases/gcc-install.sh == http* ]]
+++ GCC_INSTALL_SCRIPT_DOWNLOAD=https://github.com/fem-on-colab/fem-on-
colab.github.io/raw/d975b3f/releases/gcc-install.sh
+++ GCC_INSTALL_SCRIPT_PATH=/tmp/gcc-install.sh
+++ [[ ! -f /tmp/gcc-install.sh ]]
+++ source /tmp/gcc-install.sh
++++ set -e
++++ set -x
++++ INSTALL_PREFIX=/usr/local
+++++ echo /usr/local
+++++ awk -F/ '{print NF-1}'
+++++ INSTALL_PREFIX_DEPTH=2
+++++ PROJECT_NAME=fem-on-colab
+++++ SHARE_PREFIX=/usr/local/share/fem-on-colab
+++++ GCC_INSTALLED=/usr/local/share/fem-on-colab/gcc.installed
+++++ [[ ! -L /usr/local/lib64 ]]
+++++ [[ ! -L /usr/local/lib64 ]]
+++++ [[ ! -d /usr/local/lib64 ]]
+++++ [[ ! -f /usr/local/share/fem-on-colab/gcc.installed ]]
+++ MPI4PY_ARCHIVE_PATH=https://github.com/fem-on-colab/fem-on-
colab/releases/download/mpi4py-20230406-122340-5f871c3/mpi4py-install.tar.gz
+++ [[ https://github.com/fem-on-colab/fem-on-
colab/releases/download/mpi4py-20230406-122340-5f871c3/mpi4py-install.tar.gz ==
http* ]]
+++ MPI4PY_ARCHIVE_DOWNLOAD=https://github.com/fem-on-colab/fem-on-
colab/releases/download/mpi4py-20230406-122340-5f871c3/mpi4py-install.tar.gz
+++ MPI4PY_ARCHIVE_PATH=/tmp/mpi4py-install.tar.gz
+++ wget https://github.com/fem-on-colab/fem-on-
colab/releases/download/mpi4py-20230406-122340-5f871c3/mpi4py-install.tar.gz -O
/tmp/mpi4py-install.tar.gz
--2023-04-19 21:11:54-- https://github.com/fem-on-colab/fem-on-

```

```

colab/releases/download/mpi4py-20230406-122340-5f871c3/mpi4py-install.tar.gz
Resolving github.com (github.com)... 140.82.112.3
Connecting to github.com (github.com)|140.82.112.3|:443... connected.
HTTP request sent, awaiting response... 302 Found
Location: https://objects.githubusercontent.com/github-production-release-asset-2e65be/370599515/5365ada5-8176-4bb0-a0db-7a9036589c1c?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211154Z&X-Amz-Expires=300&X-Amz-Signature=39989a2acee4e6cc2546c51a5025ce7a6e151de69d9125aebcd17ef778b2d080&X-Amz-SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-disposition=attachment%3B%20filename%3Dmpi4py-install.tar.gz&response-content-type=application%2Foctet-stream [following]
--2023-04-19 21:11:54-- https://objects.githubusercontent.com/github-production-release-asset-2e65be/370599515/5365ada5-8176-4bb0-a0db-7a9036589c1c?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211154Z&X-Amz-Expires=300&X-Amz-Signature=39989a2acee4e6cc2546c51a5025ce7a6e151de69d9125aebcd17ef778b2d080&X-Amz-SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-disposition=attachment%3B%20filename%3Dmpi4py-install.tar.gz&response-content-type=application%2Foctet-stream
Resolving objects.githubusercontent.com (objects.githubusercontent.com)... 185.199.108.133, 185.199.109.133, 185.199.110.133, ...
Connecting to objects.githubusercontent.com
(objects.githubusercontent.com)|185.199.108.133|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 8548108 (8.2M) [application/octet-stream]
Saving to: '/tmp/mpi4py-install.tar.gz'

```

```

/tmp/mpi4py-install 100%[=====>] 8.15M --.-KB/s in 0.1s

```

```

2023-04-19 21:11:55 (73.3 MB/s) - '/tmp/mpi4py-install.tar.gz' saved
[8548108/8548108]

```

```

+++ [[ /tmp/mpi4py-install.tar.gz != skip ]]
+++ tar -xzf /tmp/mpi4py-install.tar.gz --strip-components=2
--directory=/usr/local
+++ [[ /tmp/mpi4py-install.tar.gz != skip ]]
+++ command -v mpicc
/usr/local/bin/mpicc
+++ [[ /tmp/mpi4py-install.tar.gz != skip ]]
+++ MPI_LIBS=('libmca*.so*' 'libmpi*.so*' 'libompi*.so*' 'libopen-pal*.so*'
'libopen-rte*.so*' 'ompi*.so*')
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/libmca*.so*'
+++ rm -f /usr/lib/x86_64-linux-gnu/libmca_common_dstore.so.1

```

```

/usr/lib/x86_64-linux-gnu/libmca_common_dstore.so.1.0.2 /usr/lib/x86_64-linux-
gnu/libmca_common_monitoring.so /usr/lib/x86_64-linux-
gnu/libmca_common_monitoring.so.50 /usr/lib/x86_64-linux-
gnu/libmca_common_monitoring.so.50.10.0 /usr/lib/x86_64-linux-
gnu/libmca_common_ompio.so /usr/lib/x86_64-linux-gnu/libmca_common_ompio.so.41
/usr/lib/x86_64-linux-gnu/libmca_common_ompio.so.41.19.3 /usr/lib/x86_64-linux-
gnu/libmca_common_sm.so /usr/lib/x86_64-linux-gnu/libmca_common_sm.so.40
/usr/lib/x86_64-linux-gnu/libmca_common_sm.so.40.20.0 /usr/lib/x86_64-linux-
gnu/libmca_common_verbs.so /usr/lib/x86_64-linux-gnu/libmca_common_verbs.so.40
/usr/lib/x86_64-linux-gnu/libmca_common_verbs.so.40.20.0
+++ ln -fs /usr/local/lib/libmca_common_dstore.so
/usr/local/lib/libmca_common_dstore.so.1
/usr/local/lib/libmca_common_dstore.so.1.0.2
/usr/local/lib/libmca_common_monitoring.so
/usr/local/lib/libmca_common_monitoring.so.50
/usr/local/lib/libmca_common_monitoring.so.50.20.0
/usr/local/lib/libmca_common_ompio.so /usr/local/lib/libmca_common_ompio.so.41
/usr/local/lib/libmca_common_ompio.so.41.29.4 /usr/local/lib/libmca_common_sm.so
/usr/local/lib/libmca_common_sm.so.40 /usr/local/lib/libmca_common_sm.so.40.30.0
/usr/local/lib/libmca_common_verbs.so /usr/local/lib/libmca_common_verbs.so.40
/usr/local/lib/libmca_common_verbs.so.40.30.0 /usr/lib
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/libmpi*.so*'
+++ rm -f /usr/lib/x86_64-linux-gnu/libmpi_cxx.so /usr/lib/x86_64-linux-
gnu/libmpi_cxx.so.40 /usr/lib/x86_64-linux-gnu/libmpi_cxx.so.40.20.1
/usr/lib/x86_64-linux-gnu/libmpi_java.so /usr/lib/x86_64-linux-
gnu/libmpi_java.so.40 /usr/lib/x86_64-linux-gnu/libmpi_java.so.40.20.0
/usr/lib/x86_64-linux-gnu/libmpi_mpifh.so /usr/lib/x86_64-linux-
gnu/libmpi_mpifh.so.40 /usr/lib/x86_64-linux-gnu/libmpi_mpifh.so.40.20.2
/usr/lib/x86_64-linux-gnu/libmpi++.so /usr/lib/x86_64-linux-gnu/libmpi.so
/usr/lib/x86_64-linux-gnu/libmpi.so.40 /usr/lib/x86_64-linux-
gnu/libmpi.so.40.20.3 /usr/lib/x86_64-linux-gnu/libmpi_usempif08.so
/usr/lib/x86_64-linux-gnu/libmpi_usempif08.so.40 /usr/lib/x86_64-linux-
gnu/libmpi_usempif08.so.40.21.0 /usr/lib/x86_64-linux-
gnu/libmpi_usempi_ignore_tkr.so /usr/lib/x86_64-linux-
gnu/libmpi_usempi_ignore_tkr.so.40 /usr/lib/x86_64-linux-
gnu/libmpi_usempi_ignore_tkr.so.40.20.0
+++ ln -fs /usr/local/lib/libmpi_cxx.so /usr/local/lib/libmpi_cxx.so.40
/usr/local/lib/libmpi_cxx.so.40.30.1 /usr/local/lib/libmpi_mpifh.so
/usr/local/lib/libmpi_mpifh.so.40 /usr/local/lib/libmpi_mpifh.so.40.30.0
/usr/local/lib/libmpi.so /usr/local/lib/libmpi.so.40
/usr/local/lib/libmpi.so.40.30.5 /usr/local/lib/libmpi_usempif08.so
/usr/local/lib/libmpi_usempif08.so.40 /usr/local/lib/libmpi_usempif08.so.40.30.0
/usr/local/lib/libmpi_usempi_ignore_tkr.so
/usr/local/lib/libmpi_usempi_ignore_tkr.so.40
/usr/local/lib/libmpi_usempi_ignore_tkr.so.40.30.0 /usr/lib
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/libompi*.so*'

```

```

+++ rm -f /usr/lib/x86_64-linux-gnu/libompitrace.so /usr/lib/x86_64-linux-
gnu/libompitrace.so.40 /usr/lib/x86_64-linux-gnu/libompitrace.so.40.20.0
+++ ln -fs /usr/local/lib/libompitrace.so /usr/local/lib/libompitrace.so.40
/usr/local/lib/libompitrace.so.40.30.1 /usr/lib
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/libopen-pal*.so*'
+++ rm -f /usr/lib/x86_64-linux-gnu/libopen-pal.so /usr/lib/x86_64-linux-
gnu/libopen-pal.so.40 /usr/lib/x86_64-linux-gnu/libopen-pal.so.40.20.3
+++ ln -fs /usr/local/lib/libopen-pal.so /usr/local/lib/libopen-pal.so.40
/usr/local/lib/libopen-pal.so.40.30.3 /usr/lib
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/libopen-rte*.so*'
+++ rm -f /usr/lib/x86_64-linux-gnu/libopen-rte.so /usr/lib/x86_64-linux-
gnu/libopen-rte.so.40 /usr/lib/x86_64-linux-gnu/libopen-rte.so.40.20.3
+++ ln -fs /usr/local/lib/libopen-rte.so /usr/local/lib/libopen-rte.so.40
/usr/local/lib/libopen-rte.so.40.30.3 /usr/lib
+++ for MPI_LIB in "${MPI_LIBS[@]}"
+++ rm -f '/usr/lib/mpi*.so*'
+++ rm -f '/usr/lib/x86_64-linux-gnu/mpi*.so*'
+++ ln -fs /usr/local/lib/mpi_monitoring_prof.so /usr/lib
+++ mkdir -p /usr/local/share/fem-on-colab
+++ touch /usr/local/share/fem-on-colab/mpi4py.installed
++ H5PY_ARCHIVE_PATH=https://github.com/fem-on-colab/fem-on-
colab/releases/download/h5py-20230406-124653-5f871c3/h5py-install.tar.gz
++ [[ https://github.com/fem-on-colab/fem-on-
colab/releases/download/h5py-20230406-124653-5f871c3/h5py-install.tar.gz ==
http* ]]
++ H5PY_ARCHIVE_DOWNLOAD=https://github.com/fem-on-colab/fem-on-
colab/releases/download/h5py-20230406-124653-5f871c3/h5py-install.tar.gz
++ H5PY_ARCHIVE_PATH=/tmp/h5py-install.tar.gz
++ wget https://github.com/fem-on-colab/fem-on-
colab/releases/download/h5py-20230406-124653-5f871c3/h5py-install.tar.gz -O
/tmp/h5py-install.tar.gz
--2023-04-19 21:11:55-- https://github.com/fem-on-colab/fem-on-
colab/releases/download/h5py-20230406-124653-5f871c3/h5py-install.tar.gz
Resolving github.com (github.com)... 20.27.177.113
Connecting to github.com (github.com)|20.27.177.113|:443... connected.
HTTP request sent, awaiting response... 302 Found
Location: https://objects.githubusercontent.com/github-production-release-
asset-2e65be/370599515/448f53d1-28bc-498a-a6fe-2a70ad1f8619?X-Amz-
Algorithm=AWS4-HMAC-SHA256&X-Amz-
Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-
east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211156Z&X-Amz-Expires=300&X-Amz-S
ignature=bc1a8dc28fd204bff34b191be31763eb89983044587461cb767f92adaab35fd9&X-Amz-
SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-
disposition=attachment%3B%20filename%3Dh5py-install.tar.gz&response-content-
type=application%2Foctet-stream [following]
--2023-04-19 21:11:56-- https://objects.githubusercontent.com/github-

```

```

production-release-
asset-2e65be/370599515/448f53d1-28bc-498a-a6fe-2a70ad1f8619?X-Amz-
Algorithm=AWS4-HMAC-SHA256&X-Amz-
Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-
east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211156Z&X-Amz-Expires=300&X-Amz-S
ignature=bc1a8dc28fd204bff34b191be31763eb89983044587461cb767f92adaab35fd9&X-Amz-
SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-
disposition=attachment%3B%20filename%3Dh5py-install.tar.gz&response-content-
type=application%2Foctet-stream
Resolving objects.githubusercontent.com (objects.githubusercontent.com)...
185.199.108.133, 185.199.109.133, 185.199.110.133, ...
Connecting to objects.githubusercontent.com
(objects.githubusercontent.com)|185.199.108.133|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 12321419 (12M) [application/octet-stream]
Saving to: '/tmp/h5py-install.tar.gz'

```

```

/tmp/h5py-install.t 100%[=====] 11.75M --.-KB/s in 0.1s

```

```

2023-04-19 21:11:56 (105 MB/s) - '/tmp/h5py-install.tar.gz' saved
[12321419/12321419]

```

```

++ [[ /tmp/h5py-install.tar.gz != skip ]]
++ rm -rf '/usr/lib/python*/*-packages/h5py*'
++ rm -rf /usr/local/lib/python3.9/dist-packages/h5py
/usr/local/lib/python3.9/dist-packages/h5py-3.8.0.dist-info
/usr/local/lib/python3.9/dist-packages/h5py.libs
++ tar -xzf /tmp/h5py-install.tar.gz --strip-components=2 --directory=/usr/local
++ mkdir -p /usr/local/share/fem-on-colab
++ touch /usr/local/share/fem-on-colab/h5py.installed
+ apt install -y -qq libblas-dev liblapack-dev
liblapack-dev is already the newest version (3.9.0-1build1).
Suggested packages:
  liblapack-doc
The following NEW packages will be installed:
  libblas-dev libblas3
0 upgraded, 2 newly installed, 0 to remove and 24 not upgraded.
Need to get 288 kB of archives.
After this operation, 1,589 kB of additional disk space will be used.
Selecting previously unselected package libblas3:amd64.
(Reading database ... 122352 files and directories currently installed.)
Preparing to unpack .../libblas3_3.9.0-1build1_amd64.deb ...
Unpacking libblas3:amd64 (3.9.0-1build1) ...
Selecting previously unselected package libblas-dev:amd64.
Preparing to unpack .../libblas-dev_3.9.0-1build1_amd64.deb ...
Unpacking libblas-dev:amd64 (3.9.0-1build1) ...
Setting up libblas3:amd64 (3.9.0-1build1) ...
Setting up libblas-dev:amd64 (3.9.0-1build1) ...

```

```

Processing triggers for libc-bin (2.31-0ubuntu9.9) ...
/sbin/ldconfig.real: /usr/local/lib/libblosc2.so.2 is not a symbolic link

+ PETSC4PY_ARCHIVE_PATH=https://github.com/fem-on-colab/fem-on-
colab/releases/download/petsc4py-20230406-130535-5f871c3-real/petsc4py-
install.tar.gz
+ [[ https://github.com/fem-on-colab/fem-on-
colab/releases/download/petsc4py-20230406-130535-5f871c3-real/petsc4py-
install.tar.gz == http* ]]
+ PETSC4PY_ARCHIVE_DOWNLOAD=https://github.com/fem-on-colab/fem-on-
colab/releases/download/petsc4py-20230406-130535-5f871c3-real/petsc4py-
install.tar.gz
+ PETSC4PY_ARCHIVE_PATH=/tmp/petsc4py-install.tar.gz
+ wget https://github.com/fem-on-colab/fem-on-
colab/releases/download/petsc4py-20230406-130535-5f871c3-real/petsc4py-
install.tar.gz -O /tmp/petsc4py-install.tar.gz
--2023-04-19 21:12:07-- https://github.com/fem-on-colab/fem-on-
colab/releases/download/petsc4py-20230406-130535-5f871c3-real/petsc4py-
install.tar.gz
Resolving github.com (github.com)... 140.82.113.3
Connecting to github.com (github.com)|140.82.113.3|:443... connected.
HTTP request sent, awaiting response... 302 Found
Location: https://objects.githubusercontent.com/github-production-release-
asset-2e65be/370599515/6aebdbcb-66c8-4575-8da1-7ff18ff22cfa?X-Amz-
Algorithm=AWS4-HMAC-SHA256&X-Amz-
Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-
east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211207Z&X-Amz-Expires=300&X-Amz-S
ignature=e728ce83331be54b702938e08e304bcaf62e17312c781b7c04c101857fef2807&X-Amz-
SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-
disposition=attachment%3B%20filename%3Dpetsc4py-install.tar.gz&response-content-
type=application%2Foctet-stream [following]
--2023-04-19 21:12:07-- https://objects.githubusercontent.com/github-
production-release-
asset-2e65be/370599515/6aebdbcb-66c8-4575-8da1-7ff18ff22cfa?X-Amz-
Algorithm=AWS4-HMAC-SHA256&X-Amz-
Credential=AKIAIWNJYAX4CSVEH53A%2F20230419%2Fus-
east-1%2Fs3%2Faws4_request&X-Amz-Date=20230419T211207Z&X-Amz-Expires=300&X-Amz-S
ignature=e728ce83331be54b702938e08e304bcaf62e17312c781b7c04c101857fef2807&X-Amz-
SignedHeaders=host&actor_id=0&key_id=0&repo_id=370599515&response-content-
disposition=attachment%3B%20filename%3Dpetsc4py-install.tar.gz&response-content-
type=application%2Foctet-stream
Resolving objects.githubusercontent.com (objects.githubusercontent.com)...
185.199.108.133, 185.199.109.133, 185.199.110.133, ...
Connecting to objects.githubusercontent.com
(objects.githubusercontent.com)|185.199.108.133|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 155154171 (148M) [application/octet-stream]
Saving to: '/tmp/petsc4py-install.tar.gz'

```



```
/tmp/petsc4py-insta 100%[=====>] 147.97M 149MB/s in 1.0s
```

```
2023-04-19 21:12:08 (149 MB/s) - '/tmp/petsc4py-install.tar.gz' saved  
[155154171/155154171]
```

```
+ [[ /tmp/petsc4py-install.tar.gz != skip ]]  
+ tar -xzf /tmp/petsc4py-install.tar.gz --strip-components=2  
--directory=/usr/local  
+ mkdir -p /usr/local/share/fem-on-colab  
+ touch /usr/local/share/fem-on-colab/petsc4py.installed
```

This code imports the numpy library as “np” and the MPI library from “mpi4py” module. It then initializes the MPI communication world, retrieves the number of processes and the rank of the current process.

```
[3]: import numpy as np  
      from mpi4py import MPI  
  
      comm = MPI.COMM_WORLD  
      nprocs = comm.Get_size()  
      rank = comm.Get_rank()
```

Now, we will create our class `SparseMatrix`

The class will represent a sparse matrix in COO format.

it should also keep track of the shape of the matrix.

You need to add the necessary attributes to your class to account for the aforementioned requirements

Let’s start with the `__init__` method of our class:

it should take one additional argument `arg` that will represent the various objects from which we can instantiate our class.

First, we should be able to construct an instance of our class from a regular `numpy` 2d array.

Inside the `__init__` method, check if `arg` is an instance of a `numpy` array.

Then, check if the provided array represents a valid matrix.

If it is not the case, an exception should be raised

The code begins by defining a class called `SparseMatrix`. The class has an initialization method that expects a `numpy` array as an argument named ‘arg’. The code then verifies if the input argument is a `numpy` array and whether it has a valid matrix shape (i.e., 2D). If any of these checks fail, the code raises an appropriate exception.

```
[4]: class SparseMatrix:  
      def __init__(self, arg):  
          if type(arg) is not np.ndarray:  
              raise TypeError('The Input is not a Numpy array')  
          if len(arg.shape) != 2:  
              raise ValueError("invalid Matrix")
```

Next, we should be able to construct an instance of our class from a tuple of 3 `numpy` arrays representing a matrix in COO format (x, Y, Values)

Extend the `__init__` method by checking if `arg` is an instance of this case. Then, check if the provided array represents a valid matrix. If it is not the case, an exception should be raised

The code introduces a class named `SparseMatrixCOO` that has an `init` method accepting a tuple containing three `numpy` arrays representing a matrix in COO format. It verifies the correctness of the input by ensuring that it is a tuple with exactly three `numpy` arrays.

Additionally, it checks whether every element in the tuple is a `numpy` array. Moreover, it defines a method called `print_coo` that prints the three `numpy` arrays in COO format.

```
[34]: class SparseMatrix:
    def __init__(self, arg):
        self.row , self.col , self.data = arg

        if type(arg) is not tuple:
            raise TypeError("The input must be a tuple")
        if len(arg) != 3 :
            raise ValueError("Invalid COO format, the input tuple must contain_
↪3 np.arrays (row,col,data)")
        i = 0
        while i+1 < len(arg):
            if len(arg[i]) != len(arg[i+1]):
                raise ValueError('The lists must have the same size')
            i +=1
        for lis in arg:
            if type(lis) is not np.ndarray:
                raise TypeError('The elements inside the input are not a Numpy_
↪arrays')
```

Create a function `cooTranspose` that takes an instance of our class `SparseMatrix` and returns its transpose.

The `cooTranspose` function transposes a `SparseMatrixCOO` object by swapping its row and column indices. The function then returns the transposed object.

```
[6]: def cooTranspose(a):
    a.row , a.col = a.col , a.row
    return a
```

Create a function `cooMatVec` that takes an instance of our class `SparseMatrix` and a vector as a `numpy` array and returns their product.

The code defines a function called `cooMatVec` that takes an instance of the `SparseMatrix` class and a vector as a `numpy` array and returns their product.

```
[7]: def cooMatVec(A, x):
    if len(A.col) != len(x) :
```

```

        raise ValueError('Wrong shape input')

    vec = [0] * len(A.row) # Initialize vec to all zeros
    for i in range(len(A.data)):
        vec[A.row[i]] += A.data[i] * x[A.col[i]]
    return vec

```

Create a function `cooMatMat` that takes two instances of our class `SparseMatrix` and returns their matrix product as a 2 dimensional numpy array

The function `cooMatMat` takes two `SparseMatrix` instances as input and returns their product as a numpy array using a nested loop implementation of matrix multiplication. It verifies the shape compatibility of the input matrices before computing their product.

```

[8]: def CoMatMat(A, B):
    C = np.zeros((len(A.row), len(B.col)))

    #checking if the input matrixes can be multiplied by verifying the
    ↪compatibility of their shape
    if len(A.col) != len(B.row) :
        raise ValueError("Wrong shape input, the number of columns of first
    ↪matrix is'nt matching number of rows of second matrix")

    data_a = A.data
    row_a = A.row
    col_a = A.col
    data_b = B.data
    row_b = B.row
    col_b = B.col

    for i, j, v in zip(row_a, col_a, data_a):
        for k, l, w in zip(row_b, col_b, data_b):
            if j == k:
                C[i, l] += v * w

    return C

```

1 Part 2

In this part, we will be solving a system of linear equations involving a sparse matrix `A` in parallel. You will not have to solve the system. However, you will have to implement the function `CreateLocalMatVec` that sets the system for the class `LinearSystem`. At the end, compare the results and explain any discrepancies.

```

[9]: #Create the matrix and Rhs
np.random.seed(42)
from scipy.sparse import random
if rank == 0:
    n = 100

```

```

# Set parameters for the sparse matrix
density = 0.3 # density of non-zero elements (between 0 and 1)
A = random(n, n, density=density, format='csr')
x = np.random.rand(n)
B_all = np.dot(A.toarray(),x)
else:
    A = None
    B_all = None

```

```

[10]: def CreateLocalMatVec(A, B_all):
    if rank == 0:

        shape = A.shape
        nrows = shape[0]
        # split the number of rows evenly (as possible) among the MPI tasks
        N_pertask, extra = divmod(nrows, nprocs)

        # count: the size of each sub-task
        count = [N_pertask + 1 if i < extra else N_pertask for i in
↪range(nprocs)]

        # displacement: the starting index of each sub-task
        displ = [sum(count[:i]) for i in range(nprocs)]

        #---- Send the relevant subsets of A and B to each slave MPI task ----
        for i in range(1,nprocs):

            # Get the start and end row index for this MPI task
            rstart = displ[i]
            rend    = rstart + count[i]

            #---- Get the subsets of A and B using these rows ----
            A_indptr = np.array(A.indptr[rstart:rend+1] - A.indptr[rstart])
            # modified row-pointer array that will be consistent on the MPI task
            pstart   = A.indptr[rstart] # starting row-pointer index
            pend      = A.indptr[rend]   # end      row-pointer index

            A_indices = np.array(A.indices[pstart:pend])
            A_data     = np.array(A.data[pstart:pend])
            B           = np.array(B_all[rstart:rend])

            # Save the lengths of each array
            lengths = {
                'A_indptr' : len(A_indptr),
                'A_indices': len(A_indices),
                'A_data'   : len(A_data),

```

```

        'B'          : len(B)
    }

    # Send the arrays and their lengths to the relevant MPI task
    comm.send(lengths,dest=i)
    comm.Send(A_indptr,dest=i)
    comm.Send(A_indices,dest=i)
    comm.Send(A_data,dest=i)
    comm.Send(B,dest=i)

    #---- Set the relevant subsets of A and B for the master MPI task
    ↪(we don't need to do an MPI Send)
    rstart = displ[0]
    rend   = rstart + count[0]

    A_indptr = np.array(A_indptr[rstart:rend+1] - A_indptr[rstart])
    pstart   = A_indptr[rstart]
    pend     = A_indptr[rend]

    A_indices = np.array(A_indices[pstart:pend])
    A_data    = np.array(A_data[pstart:pend])
    B         = np.array(B_all[rstart:rend])
else:
    # Receive the array lengths
    lengths = comm.recv(source=0)
    # Initialise the buffers
    A_indptr = np.empty(lengths['A_indptr'], dtype=np.int32)
    A_indices = np.empty(lengths['A_indices'], dtype=np.int32)
    A_data    = np.empty(lengths['A_data'], dtype=A.dtype)
    B         = np.empty(lengths['B'], dtype=B_all.dtype)
    # Receive the arrays
    comm.Recv(A_indptr,source=0)
    comm.Recv(A_indices,source=0)
    comm.Recv(A_data,source=0)
    comm.Recv(B,source=0)

    shape = None

    # broadcast shape
    shape = comm.bcast(shape, root=0)

    return (A_indptr, A_indices, A_data, B, shape)

```

```

[11]: class LinearSystem():
    def __init__(self, A=None, shape=None, rhs=None, solver=None, comm=None):

        from petsc4py import PETSc

```

```

self.opts = PETSc.Options()

self.ksp = PETSc.KSP()
self.ksp.create()

mat = PETSc.Mat().createAIJ(comm=comm, size=shape, csr=A)
mat.setUp()
mat.assemblyBegin()
mat.assemblyEnd()
self.sol, self.rhs = mat.getVecs()
self.rhs.setArray(rhs)

#---- Set up solver ----
self.ksp = PETSc.KSP().create(comm=comm)

# It is commonly used with the direct solver preconditioners like PCLU
↳and PCCHOLESKY
self.ksp.setType('preonly')
pc = self.ksp.getPC()
pc.setType('lu')
pc.setFactorSolverType(solver)

self.ksp.setOperators(mat)
self.ksp.setFromOptions() # Apply any command line options
self.ksp.setUp()

def solve(self):
    # st=timeit.default_timer()
    self.ksp.solve(self.rhs, self.sol)

```

```

[12]: (A_indptr, A_indices, A_data, b, shape) = CreateLocalMatVec(A, B_all)

L = LinearSystem(A=(A_indptr, A_indices, A_data), rhs=b, shape=shape,
↳solver="mumps")
ts = MPI.Wtime()
L.solve()
te = MPI.Wtime()
tt = comm.reduce(te - ts, op=MPI.MAX, root=0)
if rank == 0:
    print("Timing to solve the linear system with petsc", tt)

```

Timing to solve the linear system with petsc 0.0009621679999999994

```

[13]: #---- Gather the solution onto a single array on the master MPI task
if rank == 0:
    X = np.empty(shape[0], dtype=np.double)

```

```
else:
    X = None
comm.Gatherv(L.sol.array,X)
```

```
[35]: np.random.seed(42)
if rank == 0:
    A_coo = A.tocoo()
    B = SparseMatrix((A_coo.row,A_coo.col,A_coo.data))

    from scipy import sparse
    from scipy.sparse.linalg import spsolve
    mat = sparse.csr_matrix((B.data, (B.row, B.col)))
    ts = MPI.Wtime()
    sol = spsolve(mat, b)
    te = MPI.Wtime()
    print("Timing to solve the linear system with spsolve", te - ts)
```

Timing to solve the linear system with spsolve 0.001159788999984812

```
[36]: if rank == 0:
    print(np.allclose(X,sol))
```

True