MENG 25510 Final Report: Hartree-Fock on HeH^+ with 6-311G

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(Dated: 30 May 2022)

Please see the corresponding code at `https://github.com/FitzSW/HF_HeH` for this project.

I. INTRODUCTION

This is a reference document to go with our submission for the MENG 25510 final coding project, for which we chose to implement the Hartree-Fock (HF) Self-Consistent Field (SCF) method on a HeH^+ molecular system using the 6-311G basis set on both atoms. The geometry at which we performed the calculation was optimized at the CCSD/aug-cc-pZTZ level of theory using Gaussian 16[1]. The result of our code is then compared to an energy found with PySCF[2–4] using the same geometry and basis set.

II. HARTREE-FOCK ALGORITHM AND CODE DETAILS

We closely follow the suggested implementation scheme given in Szabo and Ostlund[5], in which explicit formulas and matrix algorithms are given. Any of the following formulas can be found in this reference text if not explicitly stated otherwise.

A. Program Control Flow

First, the input geometry and basis set files are read into the main program (`main.f90`), which are then used to construct a 1D array of the "orbitals" derived type (written in `orbitals.f90`), which each include the name of its host atom, the orbital angular momentum type (e.g. "s"), the coordinates of the host atom, the length of the contraction, as well as arrays of coefficients and exponential factors for the contraction.

From here, we then calculate the stored integrals to populate the matrices $\mathbf{S}$, $\mathbf{T}$, $\{\mathbf{V}^{\text{nuc.}}\}$, and $\mathbf{TE}$, with the last representing the two-electron integrals. The eigenvalue problem that we are trying to solve is recommended to be handled via a transformation to a set of orthogonalized orbitals via a matrix $\mathbf{X}$ obtained from the *symmetric orthogonalization* scheme

$$\mathbf{X} = \mathbf{S}^{-1/2} \tag{1}$$

The necessary matrix computations are done with assistance from the C++ numerics library Eigen[6], which is also later used to find the eigenvalues and eigenvectors of matrices at each cycle of the SCF procedure when solving

$$\mathbf{F}'\mathbf{C}' = \mathbf{C}'\varepsilon \tag{2}$$

with $\mathbf{F}'$ as the transformed Fock matrix, $\mathbf{C}'$ as the transformed coefficient matrix, and ε as a diagonal matrix of orbital energies.

After the transformed coefficient matrix is found, it is reverted back to the original basis via $\mathbf{C} = \mathbf{X}\mathbf{C}'$. A real attempt at the density matrix $\mathbf{P}$ can now be found, as well as $\mathbf{G}$ for the next cycle of the SCF procedure using a new Fock matrix. This cycle is repeated iteratively until the largest change in any element of the density matrix is less than 10^{-4}. Finally, once we have obatained converged matrices, a numerical value for the ground state electronic energy of the occupied molecular orbital is

$$E_0^{\text{elec.}} = \frac{1}{2}\sum_{\mu\nu}\mathbf{P}_{\nu\mu}\left(\mathbf{H}_{\mu\nu}^{\text{core}} + \mathbf{F}_{\mu\nu}\right) \tag{3}$$

which can then be added to the nuclear repulsion energy $E_0 = E_0^{\text{elec.}} + E_0^{\text{nuc.}}$.

III. USE AND INSTALLATION

In order to run our code, please clone the git repository that is linked in the abstract of this document. These instructions will assume that you are on a *nix system (i.e. you have access to `wc` and `rm` as system commands) and have `gfortran` and a C++ compiler such as `clang` that has access to the Eigen header files.[7] Then, inside the cloned directory, run the command:

```
./build.sh
```

to build and execute the project. The results of the SCF procedure will be written to file in `hf_out.out`.

IV. RESULTS AND DISCUSSION

V. CONCLUSION

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[4]Q. Sun, "Libcint: An efficient general integral library for gaussian basis functions," J. Comp. Chem. **36**, 1664–1671 (2015), https://onlinelibrary.wiley.com/doi/pdf/10.1002/jcc.23981.
[5]A. Szabo and N. S. Ostlund, *Modern quantum chemistry: introduction to advanced electronic structure theory* (Courier Corporation, 2012).
[6]G. Guennebaud, B. Jacob, *et al.*, "Eigen v3," http://eigen.tuxfamily.org (2010).
[7]If you don't have the header files, then find them here `https://gitlab.com/libeigen/eigen` and place the directory "Eigen" in the same directory as the Matrix_IO files, then run the command `./eigen_adaptor.sh`.