This is a multiple choice exam. Circle the correct answer.

There is one correct answer to every problem. There is no partial credit.

Atomic numbers are: H, 1; C, 6; O, 8; F, 9.

You should try to go through all the problems first, saving harder ones for later.

There are 20 problems. Each is worth 5 points.

There is no penalty for guessing.

Please write your name at the bottom of each page.

Please mark your exam with a pen, not a pencil. Do not use correction fluid to change an answer. Cross your old answer out and circle the correct answer. Exams marked with pencil or correction fluid will not be eligible for regrade under any circumstances.

Score on Next Page after Grading

NAME: ________________________________________________________________
1. Which of the following statements is/are false about a Hamiltonian that is separable into a sum of one-electron operators?

(a) Its eigenfunctions can be normalized
(b) Its eigenfunctions can be made to be antisymmetric
(c) It can include electron-electron repulsion only in an average way
(d) It cannot include the kinetic energy operator
(e) Its eigenvalues can be determined from the eigenvalues of the one-electron operators
(f) Its eigenfunctions are formed from Hartree products of the one-electron eigenfunctions
(g) It can include electron-electron repulsion only in an average way
(h) None of the above

2. An operator \( H = h_1 + h_2 + h_3 \) where \( h_1 \psi_1 = 3 \psi_1 \), \( h_2 \psi_2 = 3 \psi_2 \), and \( h_3 \psi_3 = 2 \psi_3 \). If \( \psi_1, \psi_2, \) and \( \psi_3 \) are normalized, what is \( \langle \psi_1 \psi_2 \psi_3 | H | \psi_1 \psi_2 \psi_3 \rangle \)?

(a) \(-2\)
(b) \(0\)
(c) \(1\)
(d) \(2 \frac{2}{3}\)
(e) \(\pi\)
(f) \(8\)
(g) \(18\)
(h) None of the above

3. Which of the below is not the Coulomb integral \( J_{ab} \) between an electron in orbital \( a \) and another electron in orbital \( b \)?

(a) \( \iiint a^*(1)b^*(2) \frac{1}{\eta_1^2} a(1)b(2) dr_1 dr_2 \)
(b) \( \frac{1}{\eta_2^2} a(1)^2 b(2)^2 dr_1 dr_2 \)
(c) \( \iiint a^*(1)a(1)b^*(2)b(2) \frac{1}{\eta_2^2} dr_1 dr_2 \)
(d) \( \iiint a^*(1)b(2) \frac{1}{\eta_2^2} a(1)b^*(2) dr_1 dr_2 \)
(e) \( \iiint a^*(1)b^*(1) \frac{1}{\eta_2^2} a(2)b(2) dr_1 dr_2 \)
(f) \( (a(1) b(2) a(1) b(2)) \)
(g) \( \iiint |a(1)|^2 \frac{1}{\eta_2^2} |b(2)|^2 dr_1 dr_2 \)
(h) None of the above

4. When is the Coulomb integral \( J_{ab} \) equal to the exchange integral \( K_{ab} \)?

(a) When \( a \) and \( b \) have the same angular momentum
(b) When \( a = b \)
(c) When \( a \) and \( b \) are orthogonal
(d) When \( S_{ab} = 1 \)
(e) When \( a \) and \( b \) are infinitely separated
(f) (b) and (e)
(g) (b), (d), and (e)
(h) The two are never equal

NAME: ________________________________________________________________
For the next three questions, consider a Hückel theory calculation on planar neutral 1,3,5-hexatriene with carbon atoms numbered as indicated.

5. Which of the following statements is/are not true about Hückel theory in general?
   (a) The Hückel theory many-electron wave function is the Hartree product of the molecular orbitals
   (b) Hückel theory is an iterative self-consistent field procedure
   (c) The basis set is one p orbital per carbon atom, with all p orbitals parallel
   (d) For any two basis functions $S_{ij} = \delta_{ij}$
   (e) All resonance integrals in the secular determinant are replaced by either zero or empirically determined values
   (f) The final MOs are expressed as a linear combination of AOs
   (g) (a) and (d)
   (h) (b) and (f)

6. Which of the following statements is/are not true about a Hückel theory calculation for 1,3,5-hexatriene?
   (a) There are four occupied MOs in the final wave function
   (b) $H_{23} = H_{56}$
   (c) $H_{11} = S_{11}$
   (d) The terms in the secular determinant have dimension $6 \times 6$
   (e) $H_{14} = S_{14}$
   (f) (a) and (c)
   (g) (a) and (e)
   (h) (b) and (e)

7. Which of the following statements is/are true about a Hückel theory calculation on 1,3,5-hexatriene?
   (a) The only node in the lowest energy MO will be the plane of the molecule
   (b) No MO will use all 6 basis functions
   (c) MOs with more nodes will have lower kinetic energies
   (d) $H_{22} = \alpha / 2$
   (e) If there were no interaction between any of the 3 formal double bonds, the total energy would be $6\alpha + 6\beta$
   (f) The secular determinant would not change if we connected atom 1 to atom 6 to make benzene
   (g) (a) and (e)
   (h) (c), (d), and (e)
8. What distinguishes the Hartree-Fock (HF) method from the Hartree method?

(a) HF wave functions are antisymmetric and Hartree wave functions are not

(b) Only the HF method requires exchange integrals

(c) Only the HF method forms molecular orbitals as linear combinations of atomic orbitals

(d) Only the HF method accounts for the correlation between electron movements

(e) Only the HF method uses basis functions

(f) Only the HF method requires a self-consistent-field iterative procedure

(g) (a) and (b)

(h) (b) and (f)

9. How do gaussian orbital basis functions differ from Slater orbital basis functions?

(a) Gaussian orbitals cannot be normalized but Slaters can

(b) There is always an analytic solution to (μν|λσ) when all basis functions are gaussians, but not necessarily when they are Slaters

(c) Only gaussians have a cusp at the nucleus

(d) Gaussian orbitals have a slower radial decay than Slater orbitals

(e) Only gaussian orbitals are exact solutions of the Schrödinger equation for one-electron atoms

(f) Gaussian p orbitals cannot be anywhere negative but Slater p orbitals can

(g) (a) and (c)

(h) (b) and (f)

10. Consider the molecule HF (hydrogen fluoride). What is the minimum number of atomic-orbital basis functions required for a Hartree-Fock calculation on HF?

(a) 1

(b) 2

(c) 3

(d) 4

(e) 5

(f) 6

(g) 7

(h) 10
11. Which of the below statements about the density matrix $P$ in Hartree-Fock calculations is/are true?

(a) The matrix is $N \times N$ where $N$ is the number of basis functions
(b) The matrix elements depend on the coefficients of only the occupied molecular orbitals
(c) For all $m, n$, $P_{mn} = P_{nm}$
(d) To start an HF calculation, one uses a guess to construct the density matrix
(e) If $P$ is unchanged after a self-consistent-field step, the HF calculation is converged
(f) (c) and (e)
(g) (a), (d), and (e)
(h) All of the above

12. Given two normalized basis functions $\mu$ and $\nu$ where $\mu \neq \nu$, which of the below statements is/are always true?

(a) $\langle \mu | -\frac{1}{2} \nabla^2 \mu \rangle > 0$
(b) $\langle \mu | -\frac{1}{2} \nabla^2 \mu \rangle > \langle \mu | -\frac{1}{2} \nabla^2 \nu \rangle$
(c) $\langle \mu | -\frac{1}{2} \nabla^2 \nu \rangle > 0$
(d) $0 \leq S_{\mu\nu} \leq 1$
(e) $-1 \leq S_{\mu\nu} \leq 1$
(f) (a) and (c)
(g) (a), (b), and (e)
(h) All of the above

13. In a restricted Hartree-Fock calculation on methane ($\text{CH}_4$), how many occupied MOs will be used to construct the HF wave function?

(a) 1
(b) 2
(c) 3
(d) 4
(e) 5
(f) 6
(g) 7
(h) 8

14. The Hartree-Fock wavefunction for a molecule of 4 atoms is to be computed using 12 basis functions. How many one-electron integrals need to be evaluated ignoring any symmetry from the molecule or the turnover rule?

(a) $(12^2) + (4 \times 12^2) + (12^4)$
(b) $2 \times 12^2$
(c) $(12^2) + (4 \times 12^2)$
(d) 1
(e) $(12) + (4 \times 12)$
(f) $(12^2) + (4 \times 12^2) + (12^4) / 2$
(g) $\pi$
(h) $4 \times 12$
15. If each basis function in problem 14 is a contracted gaussian basis function formed from 5 primitive gaussian functions, by what factor will the total number of one-electron integrals over primitive functions exceed the number of one-electron integrals over contracted functions?

(a) 1  
(b) 4  
(c) 9  
(d) 16  
(e) 25  
(f) 36  
(g) 49  
(h) 64

16. Consider the water molecule with all atoms in the \(yz\) plane (just as in class). Which of the below integrals involving gaussian AO basis functions is/are equal to zero?

(a) \(\left\langle 1s_O \left| \frac{1}{2} \nabla^2 \right| 1s_{H_a} \right\rangle\)  
(b) \(\left\langle 2s_O \mid 1s_O \right\rangle\)  
(c) \(\left\langle 1s_{H_b} \mid 1s_{H_a} \right\rangle\)  
(d) \(\left\langle 2p_{x,O} \mid 1s_{H_a} \right\rangle\)  
(e) \(\left\langle 2p_{x,O} \mid 1s_O \right\rangle\)  
(f) (a) and (e)  
(g) (d) and (e)  
(h) All of the above

17. What is the name for any kind of surface defined by \(|\Psi|^2 = C\) where \(C\) is a constant?

(a) van der Waals surface  
(b) isopotential surface  
(c) isodensity surface  
(d) isometric surface  
(e) Lennard-Jones surface  
(f) isoenergy surface  
(g) isotired surface  
(h) reentrant surface

18. Which of the below sets of Mulliken atomic partial charges is most reasonable from a Hartree-Fock calculation on the molecule HOF (hypofluoric acid)?

(a) \(q_H = 0.7, q_O = -0.7, q_F = 0.0\)  
(b) \(q_H = 0.3, q_O = -0.7, q_F = -1.7\)  
(c) \(q_H = -0.7, q_O = 0.7, q_F = 1.0\)  
(d) \(q_H = 0.8, q_O = -0.3, q_F = -0.5\)  
(e) \(q_H = 0.1, q_O = 0.6, q_F = -0.5\)  
(f) \(q_H = 0.0, q_O = 0.0, q_F = 0.0\)  
(g) \(q_H = 1.5, q_O = -1.0, q_F = -0.5\)  
(h) \(q_H = 1.0, q_O = 1.0, q_F = 1.0\)
19. An HF/STO-3G calculation provides the following energies (a.u.) for the molecular orbitals of a molecule with 10 electrons: $-21.5, -1.6, -0.7, -0.7, -0.4, 0.6, 0.8, 1.1$. Based on Koopmans’ theorem, what is the ionization potential of the most weakly bound electron in a.u.?

(a) 1.6 (e) 1.0
(b) 0.7 (f) 0.0
(c) 0.6 (g) $\pi$
(d) 0.4 (h) $-0.6$

20. The $\pi$ aromatic system of 1-methoxynaphthalene can act as a nucleophile to trap the $t$-butyl cation, resulting in $t$-butyl substitution after loss of a proton from the ring position at which trapping occurs. Shown below are the HOMO and LUMO of 1-methoxynaphthalene (viewed from directly above, so you are looking at the top of the p orbitals of the $\pi$ system—the size of a circle indicates the importance of that AO’s contribution to the MO). Which $t$-butylated stereoisomer do you expect to predominate based on these orbitals (the ring numbering scheme is shown in the reactant)?

(a) 2-$t$-butyl-1-methoxynaphthalene (e) 6-$t$-butyl-1-methoxynaphthalene
(b) 3-$t$-butyl-1-methoxynaphthalene (f) 7-$t$-butyl-1-methoxynaphthalene
(c) 4-$t$-butyl-1-methoxynaphthalene (g) 8-$t$-butyl-1-methoxynaphthalene
(d) 5-$t$-butyl-1-methoxynaphthalene