Example Sheet 4

1. Verify the Jacobi identity for Poisson brackets,
\[ \{ f, \{ g, h \} \} + \{ g, \{ h, f \} \} + \{ h, \{ f, g \} \} = 0. \]

2. A particle with mass \( m \), position \( r \) and momentum \( p \) has angular momentum \( L = r \times p \). Evaluate \( \{ x_i, L_j \} \), \( \{ p_i, L_j \} \), \( \{ L_i, L_j \} \) and \( \{ L_i, |L|^2 \} \).

The Laplace–Runge–Lenz vector is defined as
\[ A = p \times L - mk \hat{r}, \]
where \( k \) is a constant and \( \hat{r} = r/|r| \). Show that \( \{ L_i, A_j \} = \epsilon_{ijk} A_k \). For a system described by the Hamiltonian
\[ H = \frac{|p|^2}{2m} - \frac{k}{|r|}, \]
show, using Poisson brackets, that \( A \) is conserved.

3. A particle of charge \( q \) moves in a time-independent background magnetic field \( B \). Show that \( \{ m \dot{x}_i, m \dot{x}_j \} = q \epsilon_{ijk} B_k \) and \( \{ x_i, m \dot{x}_j \} = \delta_{ij} \).

A magnetic monopole is a particle that produces a radial magnetic field of the form
\[ B = g \frac{\hat{r}}{r^2}, \]
where \( g \) is a constant and \( \hat{r} = r/|r| \). Consider a charged particle moving in the background of the magnetic monopole. Define the generalized angular momentum,
\[ J = m r \times \dot{r} - qg \hat{r}. \]
Show that \( \{ J, H \} = 0 \). Why does this imply that \( J \) is conserved?

4. In the lectures we constructed canonical transformations using generating functions. Consider canonical transformations \( q \mapsto Q(q, p), \ p \mapsto P(q, p) \) from the following perspective. Define the 2n-dimensional vector \( x = (q_1, ..., q_n, p_1, ..., p_n)^\top \) and the \( 2n \times 2n \) matrix
\[ \Omega = \begin{pmatrix} 0 & I_n \\ -I_n & 0 \end{pmatrix}, \]
where each entry is itself an \( n \times n \) matrix.

(a) Write Hamilton’s equations for \( \dot{x} \) in terms of \( \Omega \) and the Hamiltonian \( H \).
(b) Hence deduce the following equation for the vector $\mathbf{X} = (Q_1, ..., Q_n, P_1, ..., P_n)^\top$:

$$\dot{\mathbf{X}} = (J \Omega J^\top) \frac{\partial H}{\partial \mathbf{X}};$$

where $J^A_B = \partial X^A / \partial x^B$ ($A, B = 1, \ldots, 2n$) is the Jacobian matrix of the transformation. This implies that, if the Jacobian of a transformation satisfies

$$J \Omega J^\top = \Omega,$$

then Hamilton’s equations are invariant under that transformation. The transformations with such a Jacobian (said to be symplectic) are canonical.

(c) Use the above conclusion to prove that, if the Poisson bracket structure is preserved, then the transformation is canonical.

5. Show that the following transformations are canonical:

(a) $P = \frac{1}{2} (p^2 + q^2)$, \quad $Q = \arctan \left( \frac{q}{p} \right)$,

(b) $P = \frac{1}{q}$, \quad $Q = pq^2$,

(c) $P = 2\sqrt{q}(1 + \sqrt{q}\cos p) \sin p$, \quad $Q = \log (1 + \sqrt{q}\cos p)$.

6. Show that the following transformation is canonical, for any constant $\lambda$:

$$q_1 = Q_1 \cos \lambda + P_2 \sin \lambda, \quad q_2 = Q_2 \cos \lambda + P_1 \sin \lambda,$$

$$p_1 = -Q_2 \sin \lambda + P_1 \cos \lambda, \quad p_2 = -Q_1 \sin \lambda + P_2 \cos \lambda.$$

Given that the original Hamiltonian is

$$H(q, p) = \frac{1}{2} (q_1^2 + q_2^2 + p_1^2 + p_2^2),$$

determine the new Hamiltonian $H(Q, P)$. Hence solve for the dynamics, subject to the constraints $Q_2 = P_2 = 0$.

7. A group of particles, all of the same mass $m$, have initial heights $z_0$ and vertical momenta $p_0$ lying in the rectangle $-a \leq z_0 \leq a$, $-b \leq p_0 \leq b$ in phase space. The particles fall freely in a uniform gravitational field for a time $t$. Find the region of phase space in which they lie at time $t$, and show by direct calculation that its area is still $4ab$.

8. A Poisson structure on $\mathbb{R}^n$ is an antisymmetric matrix whose components $\pi^{AB}(x)$ may depend on the coordinates $x^A \in \mathbb{R}^n$, $A = 1, \ldots, n$, such that the Poisson bracket

$$\{f, g\} = \sum_{AB} \pi^{AB}(x) \frac{\partial f}{\partial x^A} \frac{\partial g}{\partial x^B}$$

satisfies the Jacobi identity.
(a) Show that
\[ \{fg,h\} = f\{g,h\} + \{f,h\}g. \]

(b) Assume that the matrix \( \pi \) is invertible, and suppose that its inverse is an antisymmetric matrix \( \omega \) whose components \( \omega_{AB}(x) \) obey \( \pi^{AB}(x) \omega_{BC}(x) = \delta^A_C \) for all \( x \). Show that \( \omega \) satisfies
\[ \partial_A \omega_{BC} + \partial_C \omega_{AB} + \partial_B \omega_{CA} = 0 \]
where \( \partial_A = \frac{\partial}{\partial x^A} \). [Hint: Note that \( \pi^{AB} = \{x^A, x^B\} \).]

(c) Set \( x^A = (x, y, z) \). Show that
\[ \{x,y\} = z, \quad \{y,z\} = x, \quad \{z,x\} = y \]
defines a Poisson structure on \( \mathbb{R}^3 \), and find Hamilton’s equations corresponding to a Hamiltonian \( H = \alpha x^2 + \beta y^2 + \gamma z^2 \), where \( \alpha, \beta \) and \( \gamma \) are non-zero constants. Is this Poisson structure invertible?

9. Explain what is meant by an adiabatic invariant for a mechanical system with one degree of freedom.

A light string passes through a small hole in the roof of a lift compartment of a very high skyscraper, and a small weight is attached to the lower end. Initially, the lift is at rest and the system behaves like a simple pendulum executing small oscillations. Construct a Hamiltonian for the system and use the theory of adiabatic invariants to discuss what happens to the frequency, linear and angular amplitudes of the motion if:

(a) the lift begins to move upwards with slowly increasing acceleration, with the string attached at the hole;

(b) the lift stays at rest, but the string is slowly withdrawn through the roof.

10. Consider a system with Hamiltonian
\[ H = \frac{p^2}{2m} + \lambda q^{2n}, \]
where \( \lambda \) is a positive constant and \( n \) is a positive integer. Show that the action variable \( I \) and the energy \( E \) are related by
\[ E = \lambda^{1/(n+1)} \left( \frac{n\pi I}{J_n} \right)^{2n/(n+1)} \left( \frac{1}{2m} \right)^{n/(n+1)}, \]
where \( J_n = \int_0^1 (1-x)^{1/2} x^{(1-2n)/2n} \ dx \).

Consider a particle that moves in a potential \( V(q) = \lambda q^4 \). Assuming that \( \lambda \) varies slowly with time, show that the particle’s total energy \( E \) is proportional to \( \lambda^{1/3} \). Conversely, in the case that \( \lambda \) is fixed, show that the period of the motion is proportional to \( (\lambda E)^{-1/4} \).
11. A pulsar of mass $m$ moves in a planar orbit around a luminous supergiant star with mass $M \gg m$. You may regard the supergiant as being fixed at the origin of a plane-polar coordinate system $(r, \theta)$, and the neutron star as moving in a central potential $V(r) = -GMm/r$. Construct the Hamiltonian for the motion, and show that $p_\theta$ and the total energy $E$ are constants of motion.

The neutron star is in a non-circular orbit with $E < 0$. Give an expression for the adiabatic invariant $J(E, p_\theta, M)$ associated with the radial motion. The supergiant is steadily losing mass in a radiatively driven wind. Show that, over a long timescale, we have $E \propto M^2$.

Eventually the supergiant becomes a supernova, throwing off its outer layers on a short timescale, and leaving behind a remnant black hole of mass $M/2$. Explain why the theory of adiabatic invariants cannot be used to calculate the new orbit.

[You may find the following integral helpful:

$$\int_{r_1}^{r_2} \left[ \left( 1 - \frac{r_1}{r} \right) \left( \frac{r_2}{r} - 1 \right) \right]^{1/2} dr = \frac{\pi}{2} \left( r_1 + r_2 \right) - \pi \sqrt{r_1 r_2},$$

where $0 < r_1 < r_2$.]

12. [Optional, based on 2010 Paper 4, Section II, Question 15D]

A system is described by the Hamiltonian $H(q, p, t)$. Define the Poisson bracket \{f, g\} of two functions $f(q, p, t)$ and $g(q, p, t)$. Show from Hamilton’s equations that \[
\frac{df}{dt} = \{f, H\} + \frac{\partial f}{\partial t}.
\]

Consider the Hamiltonian

$$H = \frac{1}{2} \left( p^2 + \omega^2 q^2 \right),$$

where $\omega = \omega(t)$, and define

$$a = \frac{p - i\omega q}{\sqrt{2\omega}}, \quad a^* = \frac{p + i\omega q}{\sqrt{2\omega}},$$

where $i^2 = -1$. Evaluate $\{a, a\}$ and $\{a, a^*\}$, and show that $\{a, H\} = -i\omega a$ and $\{a^*, H\} = i\omega a^*$. Show further that, when $f(q, p, t)$ is regarded as a function of the independent complex variables $(a, a^*)$ and of $t$, one has

$$\frac{df}{dt} = i\omega \left( a^* \frac{\partial f}{\partial a^*} - a \frac{\partial f}{\partial a} \right) - \frac{1}{2} \frac{\dot{\omega}}{\omega} \left( a \frac{\partial f}{\partial a} + a^* \frac{\partial f}{\partial a^*} \right) + \frac{\partial f}{\partial t}.$$

Deduce that, in the case $d\omega/dt = 0$, both $(\log a^* - i\omega t)$ and $(\log a + i\omega t)$ are constant during the motion.

Consider now the case in which $\omega(t)$ varies slowly with time. Writing $f = (H/\omega)$, show that the time-average of $\langle df/dt \rangle$ over one period, $(2\pi/\omega)$, is approximately zero (that is, to order $(\dot{\omega}^2, \ddot{\omega})$). [Hint: You might like to start by writing $a = A(t)e^{-i\omega t} = A(0)e^{-i\omega t} + O(\dot{\omega})$.]