

# PHYS2113 Classical Mechanics

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# 1 Introduction to Lagrangian Mechanics

## 1.1 Action

**Definition 1.1 (Action)** *Action, termed  $A$ , is defined as*

$$A = \int_{t_0}^{t_1} L \, dt. \quad (1.1.1)$$

Where  $L(q, \dot{q}) = T - V = \frac{1}{2}m\dot{q}^2 - V(q)$  is what we call the *Lagrangian*.

Note that action represents the integral over time of the Lagrangian which can be thought as the motion of the object at some point of time.[1]

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## 1.2 The Euler-Lagrange Equation

**Definition 1.2 (The Euler-Lagrange Equation)** *The Euler-Lagrange equation for a system with a single degree of freedom is*

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = 0. \quad (1.2.1)$$

### 1.2.1 Derivation

We want to find a generalised solution for the path that minimises the variational problem integral

$$S = \int_{x_1}^{x_2} f[y(x), y'(x), x] \, dx. \quad (1.2.2)$$

First, let's start off by defining that the 'right' path (path with the least action/that minimise the variational problem) to be  $y = y(x)$ , and the wrong path is just a variation of the right path known as  $Y(y(x), \alpha, \eta(x)) = y(x) + \alpha\eta(x)$ .

Since the end points of the right path and the wrong path are the same we get

$$\eta(x_1) = \eta(x_2) = 0. \quad (1.2.3)$$

Now, the variational problem interval in terms of the wrong path  $S_0$  would be

$$\begin{aligned} S_0 &= \int_{x_1}^{x_2} f(Y, Y', x) \, dx \\ &= \int_{x_1}^{x_2} f(y + \alpha\eta, y' + \alpha\eta', x) \, dx. \end{aligned} \quad (1.2.4)$$

Note that the only difference between integral  $S$  and  $S_0$  is the dependence on  $\alpha$ . So, ideally to minimise this integral, we would find the stationary point of  $S_0$  in terms of  $\alpha$ , this can be expressed as

$$\begin{aligned} \frac{dS_0}{d\alpha} &= 0 \\ &= \int_{x_1}^{x_2} \frac{\partial f}{\partial \alpha} \, dx \\ &= \int_{x_1}^{x_2} \left( \eta \frac{\partial f}{\partial y} + \eta' \frac{\partial f}{\partial y'} \right) \, dx. \end{aligned} \quad (1.2.5)$$

And now, using (1.2.3) and integration by parts, we obtain the following

$$\int_{x_1}^{x_2} \eta(x) \left( \frac{\partial f}{\partial y} - \frac{d}{dx} \frac{\partial f}{\partial y'} \right) = 0. \quad (1.2.6)$$

For non-trivial solution, we must have

$$\frac{\partial f}{\partial y} - \frac{d}{dx} \frac{\partial f}{\partial y'} = 0,$$

which is the Euler-Lagrange Equation.

**Remark 1.2.1.1** *Note that for (1.2.5), the following needs to be true for  $Y = y + \alpha\eta$ ;*

$$\frac{\partial}{\partial Y} f(Y, Y', x) = \frac{\partial}{\partial y} f(y + \alpha\eta, y' + \alpha\eta', x).$$

*The proof is simple,*

$$\begin{aligned} \frac{\partial}{\partial y} f(y + \alpha\eta, y' + \alpha\eta', x) &= f'(y + \alpha\eta, y' + \alpha\eta', x) \\ &= f'(Y, Y', x). \end{aligned}$$

### 1.2.2 Example

Refer to Taylor's<sup>1</sup> **Example 6.2** on page 222.

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## 1.3 Proof of Lagrange's Equations with Constraints

Refer to **Section 7.4** (pg 250) in Classical Mechanics by JR Taylor.

One important thing: the right path of any action must follow Newton's second law.

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## 1.4 Lagrangian Multipliers

Suppose we have a system with two variables  $x, y$ . Which are linked together with a constraint, say  $F(x, y) = C \in \mathbb{R}$ .

Now, let us introduce this function  $\lambda(t)$  (aka Lagrange multiplier), and now the E-L Equation for  $x$  becomes

$$\frac{\partial L}{\partial x} + \lambda(t) \frac{\partial F}{\partial x} = \frac{d}{dt} \frac{\partial L}{\partial \dot{x}}, \quad (1.4.1)$$

similarly, the E-L equation for  $y$  is

$$\frac{\partial L}{\partial y} + \lambda(t) \frac{\partial F}{\partial y} = \frac{d}{dt} \frac{\partial L}{\partial \dot{y}}. \quad (1.4.2)$$

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<sup>1</sup>The book 'Classical Mechanics'[2] By John R. Taylor

Now, fingers cross that we can solve the above two equations. Then we can rewrite one of the variable in terms of the other and obtain their time derivatives, e.g.

$$x = g(y), \quad (1.4.3)$$

$$\implies \dot{x} = \frac{d}{dt}g(y), \quad (1.4.4)$$

$$\implies \ddot{x} = \frac{d^2}{dt^2}g(y). \quad (1.4.5)$$

And then we can substitute them into our results from Eq. (1.4.1) & (1.4.2). If we don't drink and do maths, by now, we should just be able to obtain  $\lambda(t)$  with a little more algebra.

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## 1.5 Conservation of Energy and the Hamiltonian

Refer to section **Section 7.8** (pg 269) in Taylor's for derivation.

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## 1.6 Legendre Transform

Let's have an input system that consists of

$$\begin{aligned} F(u_1, \dots, u_n, w_1, \dots, w_n); \\ v_i = \frac{\partial F}{\partial u_i}; \\ G = \sum_{i=1}^n u_i v_i - F. \end{aligned}$$

By performing a Legendre Transform, we will get the output system that consists of

$$\begin{aligned} G(v_1, \dots, v_n, w_1, \dots, w_n); \\ u_i = \frac{\partial G}{\partial v_i}; \\ F = \sum_{i=1}^n u_i v_i - G. \end{aligned}$$


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# 2 Very Short Session on Hamiltonian Mechanics

## 2.1 From Lagrangian to Hamiltonian

Let us record that in the Lagrangian, we have a function of three dependents,

$$L = L(q_1, \dots, q_n, \dot{q}_1, \dots, \dot{q}_n, t) = T - U, \quad (2.1.1)$$

and obviously, the Euler-Lagrange equation would be

$$\frac{\partial L}{\partial q_i} = \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i}. \quad (2.1.2)$$

Also remember that the **generalised momentum** (a.k.a canonical momentum/momentum conjugate to  $q_i$ ) is given by

$$p_i = \frac{\partial L}{\partial \dot{q}_i}. \quad (2.1.3)$$

The Hamiltonian is defined as

$$H = \sum_{i=1}^n p_i \dot{q}_i - L. \quad (2.1.4)$$

If we apply the Legendre Transform to the E-L equation, we will find the Hamilton's equations

$$\dot{q}_i = \frac{\partial H}{\partial p_i}, \quad \dot{p}_i = -\frac{\partial H}{\partial q_i}. \quad (2.1.5)$$


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## 2.2 Poisson Brackets

Definition of Poisson Brackets in **canonical coordinates**  $(q_i, p_i)$  on the phase space, given two functions  $f(p_i, q_i, t)$  and  $g(p_i, q_i, t)$ , the Poisson bracket take the form [3]

$$\{f, g\} = \sum_{i=1}^N \left( \frac{\partial f}{\partial q_i} \frac{\partial g}{\partial p_i} - \frac{\partial f}{\partial p_i} \frac{\partial g}{\partial q_i} \right). \quad (2.2.1)$$

The Poisson brackets of the canonical coordinates are

$$\begin{aligned} \{q_i, q_j\} &= 0 \\ \{p_i, p_j\} &= 0 \\ \{q_i, p_j\} &= \delta_{ij}. \end{aligned}$$


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## 3 Simple Harmonic Oscillator

## References

- [1] *Action (physics)*. en. Page Version ID: 1020785959. May 2021. URL: [https://en.wikipedia.org/w/index.php?title=Action\\_\(physics\)&oldid=1020785959](https://en.wikipedia.org/w/index.php?title=Action_(physics)&oldid=1020785959) (visited on 05/31/2021).
- [2] John R. (John Robert) Taylor. *Classical mechanics*. eng. Sausalito, Calif. : [Basingstoke: University Science Books ; Palgrave, distributor], 2005. ISBN: 189138922X.
- [3] *Action (physics)*. en. Page Version ID: 1014893060. 2021. URL: [https://en.wikipedia.org/w/index.php?title=Poisson\\_bracket&oldid=1014893060](https://en.wikipedia.org/w/index.php?title=Poisson_bracket&oldid=1014893060) (visited on 07/02/2021).