What is Emergence?

Philosopher Michael Polanyi made a distinction between **Tacit Knowledge** (things we can process without any conscious effort, hence similar to "**Common Sense**") and "**Emergent Knowledge**" which is built out of the former in the same way that a house is built with bricks, but, like the house, embodies something **new** (or **emergent**) that was not there in the bricks. Once the newly emerged knowledge becomes familiar enough, it too becomes tacit, and the cycle repeats. . . . In this sense Poetry is "Emergent Language" and Physics is "Emergent Science" (understanding of how the world behaves).

Emergence of Matter

Matter, from quarks to nuclei to atoms to molecules to cells to humans to planets to stars to galaxies to the cosmos as a whole, exhibits **emergent** behaviour: at each step toward greater complexity, unexpected new attributes appear, in spite of our (often exhaustive) understanding of the properties of the simpler components. A good example is **superconductivity**, a phenomenon that appeared to violate both Common Sense and the "Known Laws of Physics" but is the result of interactions governed by Quantum Electrodynamics, the best understood physical theory in history. It took over 50 years to figure out how this happens.

Physics Vocabulary

Before we can write Poetry, we have to know some words and a little grammar – the Tacit Dimension from which new language can emerge. So it is with Physics: one must be familiar with "old" terminology before one can reach for "new" ideas. By historical tradition, Physics always starts from Classical Mechanics:

$$\boldsymbol{F} = m\,\boldsymbol{a}$$

and all the other concepts that emerge from Newton's Second Koan ...er, Law... by the grammar of calculus.

The **Emergence** of **Mechanics**

(a mathematical fantasy)

- Newton's Second Law: $\boldsymbol{F} = m\,\boldsymbol{a} = d\boldsymbol{p}/dt \equiv \dot{\boldsymbol{p}}$

[Dot Notation for Time Derivatives]

- Time Integral: $\int \boldsymbol{F}(t)\, dt = \Delta \boldsymbol{p}$

[Impulse changes Momentum]

- Dot Product with $\boldsymbol{r}$ & Path Integral: $\int \boldsymbol{F}(\boldsymbol{r}) \cdot d\boldsymbol{r} = \Delta\,(\tfrac{1}{2} m v^2)$

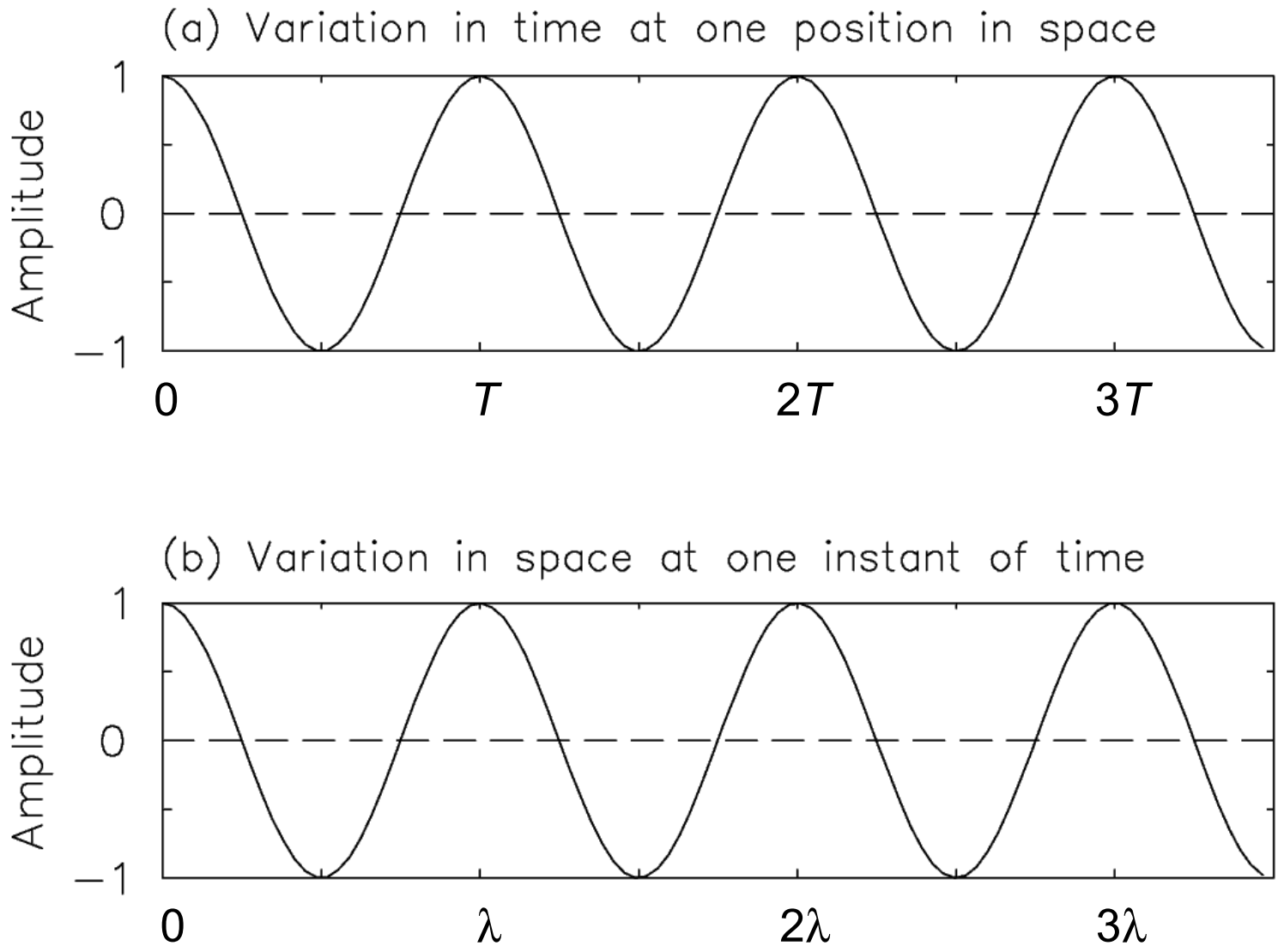
[Work changes Kinetic Energy]

- Cross Product with $\boldsymbol{r}$: $\boldsymbol{r} \times \boldsymbol{F} \equiv \tau = \boldsymbol{r} \times \dot{\boldsymbol{p}} = \dot{\ell}$

[Torque changes Angular Momentum]

Waves

Along with the vocabulary of Mechanics (concepts like force, momentum, work, energy, torque and angular momentum) we need to give names to the properties and behaviour exhibited by Waves before we can approach the emergent phenomena of Quantum Mechanics, which starts from the premise that all particles have wavelike aspects and all waves have also the properties of particles. For this we must take a little side trip. . . .


(a) Variation in time at one position in space
Amplitude
1
0
−1
0
T
2T
3T
(b) Variation in space at one instant of time
Amplitude
1
0
−1
0
λ
2λ
3λ

Wave Parameters

Frequency: $f = 1/T$ [Hz]
(inverse of Period)

Angular Frequency: $\omega = 2\pi/T$

Wavenumber: $k = 2\pi/\lambda$
(inverse of Wavelength)

Propagation Velocity: $c = \lambda f$

de Broglie's Hypothesis

The particle property is **inversely** related to the wave property with Planck's Constant of proportionality:

Momentum & **Wavelength**: $p = h/\lambda$

Energy & **Frequency**: $E = h/T$

In a sense, this is **all there is** to (nonrelativistic) Quantum Mechanics!