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Figure 1.4: A "film" of a particle in projectile motion. The 2-D frames of the film stack up to form a 3-D spacetime diagram of the situation.

Figure 1.3: Two points in the plane, with two different coordinate systems.

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Figure 1.7: The future and past light cones of event A, and various (future) light cones of events on the world line of a particle.

expanding wavefront. In spacetime, we can say that, if the particle's world line passes through the event A, the future part of the world line must lie entirely inside the future light cone of A. Similarly, the past part of the world line must lie within the past light cone of A. In other words, the light cone marks out what parts of spacetime are "accessible" from a given point (event) in spacetime by a particle passing through that point.

A 17th-Century king of Spain, thinking about his colonies in the New World, took for granted the many weeks required to send news by ship across the sea. An event that happened yesterday in Peru, though it took place in the past, could not have influenced today's events in Spain. Similarly, though tomorrow had not yet taken place, tomorrow's events in Peru could not be influenced by today's events in Spain. Such remote but nearly contemporaneous events existed in a kind of limbo, neither in the knowable past nor in the affectable future.

The limitations of the king of Spain were merely technological. We can now exchange messages between Spain and Peru in a fraction of a second. But the limitations on travel and communication imposed by the light cone structure of spacetime are inescapable. Thus, the monarch of an interstellar empire might ponder events happening this year on a planet ten light-years away. Such events are outside of the monarch's light cone, at a spacelike

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with slightly different wave 4-vectors k_1 and k_2 . The total wave is

$$\Phi = A \cos(k_1 z - \omega_1 t) + A \cos(k_2 z - \omega_2 t). \quad (6.19)$$

We can use trigonometric identities to rewrite this in a suggestive form. Write $\Delta k = k_2 - k_1$ and $\Delta \omega = \omega_2 - \omega_1$, and let $k = (k_1 + k_2)/2$ and $\omega = (\omega_1 + \omega_2)/2$ be the average wave vector and angular frequency. Then

$$\Phi = 2A \cos\left(\frac{\Delta k}{2} z - \frac{\Delta \omega}{2} t\right) \cos(kz - \omega t) \quad (6.20)$$

envelope

Thus, Φ is a wave characterized by ω and k , but "modulated" by the sinusoidal "envelope" function as shown.

Exercise 6.2 Derive The expression for Φ in Equation 6.20. Use the trigonometric identity

$$\cos(\alpha + \beta) = \cos \alpha \cos \beta - \sin \alpha \sin \beta$$

and write $k_x = k - \frac{\Delta k}{2}$, $k^+ = k + \frac{\Delta k}{2}$, etc.

A snapshot of this superposition of waves is shown in Figure 6.7. It appears as a long train of pulses. The pulses themselves (as distinct from the waves within the pulses) are described by the envelope function in Equation 6.20. This function itself has the form of a wave; the wave speed of the pulses is the group velocity:

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$$v_g = \frac{\Delta \omega}{\Delta k} \quad (6.21)$$

For small differences $\Delta \omega$ and Δk (which correspond to wide pulses in the train), we can write the group velocity as a "derivative," $v_g = \frac{d\omega}{dk}$.

In general, the physics of any sort of wave will give rise to a relationship between the angular frequency ω and the wave 3-vector k . Usually, this can be expressed by writing ω as a function of the magnitude k of the wave 3-vector: $\omega(k)$. Such a relationship is called a *dispersion relation* for the wave. Then the phase velocity v and the group velocity v_g are

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