The Spinning Rotation of Ash and Tulip Tree Samaras

Abstract. *Ash and tulip tree samaras rotate on their long axes as they fall, as well as spin around like maple samaras. They descend faster than would maple samaras of the same size and weight and much faster than would zanonia samaras, but they are very stable, which may explain their evolutionary success.*

Maple keys spin down from the trees like one-bladed autogiro rotors, as do the tiny winged seeds of many conifers (Fig. 1). Although ash and tulip keys may seem to do the same (*1*, p. 62), careful observation reveals that they rotate on their long axes as well as spinning round and round. The keys (winged seeds, or samaras) are so small and quick that the eye cannot tell the hand of this rotation. Enlarged models spin and rotate slower and show that the blade rotates on its long axis in the hand that makes its underside advance through the air faster than its top (Fig. 1).

In Fig. 2, a white-painted tulip tree (*Liriodendron tulipfera*) samara spins down in a searchlight beam in front of an open-shuttered camera. As it rotates on its axis the blade alternately shows its illuminated bottom surface and its shadowed top surface to the camera, which records a series of smeared images. A maple samara would make one image per revolution; tulip samara makes seven.

With one surface painted black, a tulip or red ash (*Fraxinus pennsylvanica*) samara looks like a Y or a cross when viewed from above or below because it rotates three or four times on its long axis for every turn about the vertical axis. White ash (*Fraxinus americana*) samaras rotate about six times.

Most ash or tulip samaras will spin in either hand.

Continuously increasing angle of attack, with the leading edge rising and moving back to become the trailing edge in endless repetition, is a stable motion of a symmetrically weighted free-falling plate. Drop a postcard and it soon settles into rotation about its long axis. The motion is well known as a powerful lift-generating mechanism, but it is little used because it produces about as much drag as lift (*2, 3*). Ailanthus (*Ailanthus altissima*) samaras descend this way, gliding at about 45° to the vertical.

Because the ash and tulip are weighted at one end, each descends in a helical path as it autorotates, a path whose radius is so small that the seed end overlaps the helix axis. This motion superposes the autogiro autorotation of the maple on the attack of autorotation of the ailanthus.

Completing the Latin square of possibilities is the Javanese cucumber (*Zanonia macrocarpa*), which does not autorotate at all. Its samaras are very light airplanes that glide in wide circles as they descend (*1*, p. 59).

In ash and tulip samaras the angle between the blade axis and the horizontal, that is, the coning angle, is set by lift and gravitational and centrifugal forces as it is in maple samaras (*4*), plus a gyroscopic precessional torque caused by the steady swinging round of the axis of blade rotation. The torque shifts the blade axis toward the vertical, which increases the coning angle and the sinking speed. To keep the axis as nearly horizontal as possible, the mass of a rotating, spinning samara should be close to the axis of blade rotation and concentrated near its ends. The blade and seed of the white ash samara are long and thin. The seed of the red ash is longer and thinner, the blade broader but thin at the edges. The edges of the tulip blade are even thinner, as are those of the European ash (*Fraxinus excelsior*) (*1*), and the blade is weighted by a pigmented spot on its axis at the end opposite the seed.

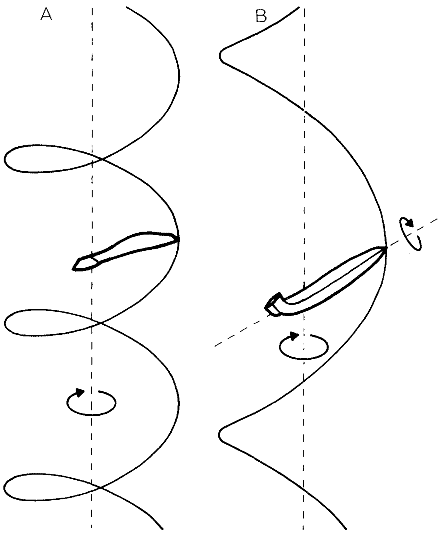

Fig. 1. (A) A Norway maple key descends like an autogiro. (B) A tulip key rotates about its long axis, which swings round and round as the key falls. The line of sight in both views slopes downward at 30° to the horizontal. The plane of the wing of a maple key is its plane of symmetry. The leading edge of the wing is weighted. The plane of symmetry of a tulip or ash key is at right angles to the plane of the wing.

The motion of tulip and ash samaras has different symmetry from that of maple samaras, which has intriguing consequences if the samaras are thrown upward. All samaras start spinning and quickly lose their upward velocity. The maple then autogiros downward with no break in its spin perceptible to the naked eye. The motion going downward is a reflection in a horizontal plane of the motion going upward. The tulip or ash stops spinning about the vertical axis, drops a dozen or more centimeters, and then starts spinning again, usually in the opposite hand. This is because reversal of the vertical motion tilts the aerodynamic force on the blade away from straight downward and gives it a component that opposes the spin. Ordinarily this brings the spin to a halt before the blade stops rotating on its long axis and starts it off in the other hand, reversing the vertical component of the force. The downward motion is an inversion of the upward motion about a point on the axis of samara spin. Occasionally it is the blade rotation rather than the spin of the samara as a whole that reverses. The downward motion is then a reflection of the upward motion in a horizontal plane. Because the aerodynamic force on the blade is in the direction given by the cross product of its rotation and velocity vectors, either rotation or spin must reverse to reverse the force from downward to upward.

The tulip, maple, ailanthus, and zanonia stratagems are in real or potential competition with each other. To com-

Table 1. Performance of samara models. "Plate" is the ailanthus model falling vertically without rotating, oriented parallel to the ground except for some wobbling. The gliding angle is the angle between the horizontal and the direction of flight. Other definitions are given in the text.

Variables	Tulip	Maple	Ailanthus	Zanonia	Plate
Sinking speed (cm/sec)	156	107	122	65	234
Cot (gliding angle) = life/drag ratio			0.98	4.94	
Airspeed (cm/sec)			171	327	
Upward force coefficient	2.55	5.43	4.19	14.75	1.13
Lift coefficient			1.49	0.569	
Drag coefficient			1.53	0.115	

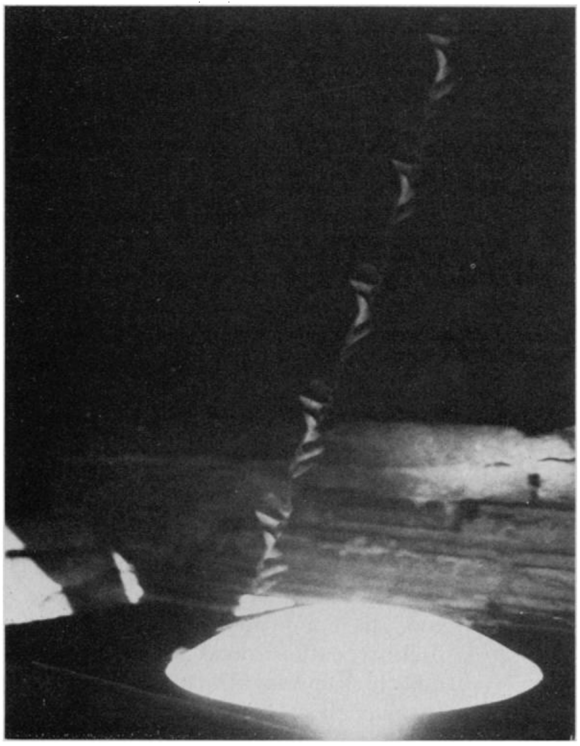

Fig. 2. A tulip key drifts in the wind as it falls toward a vertical searchlight. The camera shutter is open, the illumination steady. The key alternates between bright and dark as it shows its illuminated bottom or its shadowed top to the camera.

pare the seed-dispersing ability of the different modes of flight (as opposed to that of the actual samaras themselves, which have widely differing sizes and weights). I ballasted four wings, 12.7 by roughly 2.52 cm, cut from file cards, to about 1.2 g apiece, with the weights located so they flew like the four types of samara. The heaviest model weighed 1.36 g, the lightest 1.12 g. The widest wing was 1.036 times as wide as the narrowest. Sinking speeds, measured by ruler and stopwatch, were multiplied by

$$\left(\frac{\text{wing width}}{\text{model weight}} \times \frac{1.2}{2.52} \right)^{1/2}$$

to give the values expected for 1.2-g models with wings exactly 2.52 cm wide (Table 1).

Because the models were heavier than the samaras they flew at higher Reynolds numbers (*5*), which probably exaggerated the proportional spread in sinking speeds. Even so, except for the plate, the highest sinking speed was only 2.4 times the lowest. Sinking speed is proportional to the inverse square root of the aerodynamic forces that would be produced if each model were ballasted so all sank at the same speed. The upward force coefficient,

$$2\ (\text{weight}) \ / \ [\text{blade area} \times \text{air density} \times (\text{sinking speed})^2]$$

better measures the aerodynamic success of the design, and is proportional to the area over which a wind of varying strength and direction sows the samaras. (The length and breadth of the area are each proportional to the time the samara takes to descend, hence inversely proportional to the sinking speed.)

Lift and drag coefficients are the aerodynamic forces transverse to and parallel to the model's path, respectively, divided by half the product of air density, blade area, and the speed squared. Ailanthus has 2.62 times the lift coefficient of zanonia, at the expense of 13.3 times the drag coefficient.

Zanonia and ailanthus can add gliding distance to wind drift, but only if they fly straight. Most ailanthus seeds spiral in a helix a meter or less in diameter in one hand or the other, but some fly straighter and may serve out of proportion to their number in dispersing the species. Zanonia samaras are said to circle (*1*, p. 59), but again, a minority that flew straight could be biologically essential.

Since zanonia sinks slowest and glides farthest, why are more samaras built on the other plans? Perhaps because the others are more stable in turbulent air (the ash-tulip system being the stablest) and give performance that is less degraded by variations in shape. Ash and tulip fly in windy temperate woodlands; zanonia glides in the sheltered interior of tropical rain forests.

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References and Notes

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5. The Reynolds number for any set of objects of geometrically similar shape supported by fluid dynamic lift is proportional to [weight/(lift coefficient)]$^{1/2}$ and independent of the area of the lifting surface. Increasing the area reduces the airspeed in the same proportion, leaving the Reynolds number unchanged.
6. I thank A. Terry for help with the experiments.

11 January 1977; revised 4 March 1977

A Developmental Theory of Environmental Enrichment

Abstract. *The differential brain development induced by sensory enrichment or deprivation is most apparent in rats with low brain weights. These differences are hypothesized to represent the retarded development of environment-dependent neurons in the isolated animals.*

If animals are separated at weaning into enriched and deprived sensory environments, the enriched animals acquire larger and more complex cortices than their isolated counterparts. This enhanced cortical development includes increased cortex depth (*1*), dendritic branching (*2*), and number of glial cells (*3*).

We have recently proposed (*4*) that the mechanism responsible for this enhanced development is experience of the arousal response; such arousal is caused by both social interactions and object exploration, which provide nonspecific stimulation of cortical elements, which is, in turn, transduced into biosynthetic activity. In the following studies, we extend this concept by hypothesizing that during ontogeny, the development of some neurons can be described as environment-dependent; that is, these neurons will fully develop only in the presence of adequate amounts of sensory stimulation. The consequence is that the enrichment-isolation differences represent the extent to which normal neural development has been retarded by sensory deprivation.

Of the following nine separate studies, the first eight (groups 18, 30a, 30b, 40, 60, 80, 90, and 120) were conducted between 1968 and 1974 at the University of Queensland. The subjects were male,