What Brown saw, and you can too

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A thorough discussion is given of the original observations by Robert Brown, of particles undergoing what is now called Brownian motion. Topics scanted in the literature, the nature of those particles, and Brown's thought that he was observing universal organic particles whereas he was observing the Airy disc of his lens, are treated in detail. Also shown is how one may make the same observations, including how to make a ball lens microscope. Appendices contain tutorials on the relevant theory.

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I. INTRODUCTORY

In June 1827, the celebrated British botanist Robert Brown was observing pollen of the plant *Clarkia pulchella* immersed in water, with his one lens microscope (essentially, a magnifying glass with small diameter and large curvature). He noticed that particles ejected from the pollen were of two shapes: some were oblong and some smaller ones were circular, and they were jiggling about in the water. Thus commenced his investigations, which showed that anything sufficiently small would move similarly. Of course, we now understand, as Brown never did, that the jiggling is due to the irregular impact of water molecules.

Physicists care about particles. This paper arose from curiosity as to the nature of the particles Brown observed. That question is answered here.

Brown was motivated in his investigations by the observation, for all objects he *bruised*, that the smallest bits in motion were circular, and of about the same diameter. He called these bits "molecules" (a word in common usage meaning tiny particle), suggesting that they might be universal building blocks of nature. However, Brown was actually seeing the effects, on the images of sufficiently small objects, of the diffraction and spherical aberration of his lens. A literature search has found this point tersely suggested once[1]. An experimental and theoretical examination of this issue is given here.

Although this paper was initially intended to be brief, it grew with the realization of the richness of the subject matter, a weaving of history, botany and classical physics, with experimental possibilities. We hope that, with appropriate selectivity and emphasis, it may be an interesting and accessible resource for various projects for teachers and students from middle school to college.

Section II, History, discusses *Clarkia pulchella*. It was found by Meriwether Lewis in 1806 on the return trip of the Lewis and Clark expedition. It was named and published in 1814 in England by Frederick Traugott Pursh. Its seeds were first collected and sent to England in 1826 from the northwest Pacific coast by David Douglas. They arrived in London in 1827 and were grown there, providing flowers for Brown's investigations.

Section III, Jiggly, peruses Brown's classic paper.

Section IV is entitled Botany. The question which motivated this paper was answered only when it reached one of the authors (D. B.): the oblong particles Brown saw are amyloplasts (starch organelles, i.e., starch containers) and the spherical particles are spherosomes (lipid organelles, i.e., fat containers). Some history of early pollen research and some physiology of pollen are discussed here.

Section V, Microscopy, discusses how to go about duplicating Brown's observations of *Clarkia* pollen. This was undertaken by the author least capable in this regard, a theoretical physicist (P.P.), in expectation of uncovering difficulties that a novice might face, and is written in the first person. This is followed by a discussion of Brown's lens. It closes with an experimental investigation (by B. C.) of imaging by a 1mm diameter spherical (ball) lens, whose magnification is close to that of Brown's lens.

Section VI, Theory, is meant for advanced physics undergraduates or graduate students and their teachers. It consists of seven theoretical appendices, tutorials on classical physics. Most of this material has been known for over a century. Some of it has found its way into textbooks. Apart from the benefit of finding all the relevant material in one place, in self-contained form, each appendix contains some novel treatment. Some material may suggest further, independent, investigations. The subject matter is A) Brownian motion, B) viscous force and torque, C) WKB derivation of geometrical optics (the eikonal equation) from the wave equation, D) application to mirrors and lenses, E) Huyghens-Fresnel-Kirchhoff construction, F) imaging of a point source of light (diffraction and spherical aberration receiving a unified treatment), and G) imaging of an illuminated hole.