Mechanics of Climbing and Attachment in Twining Plants

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Twining plants achieve vertical growth by revolving around supports of different sizes on which they exert a pressure. This observation raises many intriguing questions that are addressed within the framework of elastic filamentary structures by modeling the stem close to the apex as a growing elastic rod. The analysis shows that vertical growth is achieved thanks to discrete contact points and regions with continuous contact, that the contact pressure creates tension in the stem as observed experimentally, and that there is a maximal radius of the pole around which a twiner can climb.

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Climbing plants have developed a fascinating array of mechanical strategies to achieve vertical growth without being able to support themselves. Hookers, leaners, weavers, rooters, stickers, clingers, tendril bearers, or twiners are just a few realizations of the 30 different ways vines manage to grow by taking advantage of their surrounding [1]. Twiners, such as garden peas, climbing jasmines, and morning glories, are perhaps the most studied of all vines [2]. The growing tip waves around in a circular motion known as circumnutation until it finds an appropriate upright support and then start wrapping around it to extend upward. The tip of the vine keeps nutating and the vine pursues its climbing process by forming a spiral around the support. The growth process of twining plants raises many interesting mechanical questions already noted by 19th century botanists and further studied by Silk, Holbrook, and co-workers [3–7].

Can a given twining plant climb around supports of different sizes? This question was first raised by Darwin in his book *The Movements and Habits of Climbing Plants* [8]. In the book he comments: "Most twining plants are adapted to ascend supports of moderate though of different thicknesses. Our English twiners, as far as I have seen, never twine round trees ...". As an example, Darwin noted that *Solanum dulcamara* can twine around supports of 3 mm but not on supports of 5 or 6 mm (see many other examples in [9]). The natural question is then to determine the critical cylinder radius above which a plant is no longer able to twine. In the process of establishing themselves on a pole, twining plants rely on friction [2,7]. As noted by von Sachs [10], the vines may slide off "... if the surface of their vertical support is too smooth to furnish a strong mutual friction". What is the effect of friction in the vine ability to grasp the pole? Similarly, what is the pressure generated by a plant on the pole? How does it change with its intrinsic properties and shape? Whereas most plants such as trees or flowers stems are in compression, a peculiar feature of twining plants is that their stem is in tension [4]. How is this tension generated? There is no applied load at the tip of the growing plant, gravity only increases compression and, although the stem can build compressive and tensile domains through differential growth, the net effect vanishes when averaged over the cross section. Therefore, a vine in continuous contact with a pole cannot generate tension. As we will see, tension is actually produced when the plant establishes discrete points of contacts which create anchorage points. The purpose of this Letter is to identify through simple mechanical arguments how twining vines establish themselves, develop discrete and continuous contacts, and to answer Darwin's question on the critical pole radius.

Most authors have studied the helical shape of the twining vine around the pole. By contrast, we focus on the formation of these helices by looking at the way the tip of the vine manages to grasp the pole. The vine before lignification is a long, thin, elastic filament subject to twisting and bending. Because of the small linear density of the vine and the large stresses developed through self-contact, the gravitational load on the vine has been found experimentally to be negligible by comparison to other forces involved in the problem (for instance the linear weight in *Pharbitis nil* is about $0.4\ \mathrm{mN\,cm^{-1}}$ but, it can exert a contact force of $300\ \mathrm{mN\,cm^{-1}}$ [4]). Therefore, it will be omitted in the analysis of the grasping problem. During the circumnutation process, the vine at the apex develops intrinsic curvature and torsion. We assume these curvatures to be constant and uniform. This assumption is consistent with the vertical and lateral oscillation of the vine tip observed during growth.

It is therefore reasonable to model the vine as a uniform inextensible and unshearable elastic rod with circular cross section, constant intrinsic curvature and twist, in possible contact with a cylindrical support. Since growth is slow with respect to other time scales in the problem, the attachment problem consists in finding possible equilibria of the rod on the cylinder with appropriate boundary conditions.

