This Week's Citation Classic®

All one-loop chiral gauge and gravitational anomalies are shown to cancel in the 10-dimensional N=1 supergravity theory that arises as the low-energy limit of type 1 superstring theory when the gauge group is SO(32). This cancellation follows from the absence of one-loop anomalies in the full string theory. The only other possible gauge group which gives an anomaly-free 10-dimensional chiral N= 1 supergravity theory is E_8 x E_8. [The *SCI*® indicates that this paper has been cited in more than 980 publications.]

The Consistency Of Superstring Theory

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The results in this paper were obtained in August 1984 and quickly provoked great interest since they provided evidence that certain key difficulties in unifying a theory of gravity with quantum mechanics are avoided in specific superstring theories. The paper marked the culmination of a period of collaboration between John Schwarz and myself which had started in 1979. For a few months each year we would get together in Pasadena, London, or Aspen for a period of intensive research. The subject of string theory had been developed a decade earlier but more or less abandoned in the mid-1970s due to inconsistencies that we were convinced could be overcome by incorporating supersymmetry—a symmetry of the physical laws that had been proposed in order to unify particles with integer and half integer spin.

Weobtained compelling evidence for the consistency of such "superstring" theories in a paper written in 1981[1] which showed that theories with only closed strings (type 2 theories) might avoid the disastrous infinite results typically associated with quantum theories of gravity. String theory was very different from the mainstream of the time and this result caused little comment. However, a field theory calculation[2] suggested that these theories also do not suffer from certain "anomalies," further indicating the special magic of superstring theory.

Nevertheless, the type 2 theories did not seem to be of physical interest since they do not describe the nongravitational forces in any obvious manner. Theories with open strings as well as closed ones (type 1 theories) seemed to be of more potential interest to physics. However, rather general arguments suggested that these theories would be plagued by ill-defined infinite quantities and further anomalies that would render them inconsistent. In this *Citation Classic?* paper we reported the result that there is only one anomaly-free type 1 theory, namely, that associated with a symmetry known as SO(32) (and later we showed the absence of infinities for the same theory). We explained the result in the language of quantum field theory—language that is the bread and butter of theoretical physicists—leaving the string calculation to a subsequent paper. We showed that the absence of anomalies depends on a subtle interplay between the gravitational and nongravitational forces. Furthermore, the general argument allowed another possible symmetry (in addition to SO(32)), known as E_8 x E_8, which was not allowed by any of the then-known string theories. However, a new kind of theory, the *heterotic* string, was soon developed,[3] which allowed either of the two anomaly-free symmetries.

The prospect of a unified quantum theory of all the forces sparked off intense work on "superstring phenomenology," the foundations of which were laid in a seminal 1985 paper.[4] This highlighted many seemingly miraculous features of the superstring equations that are crucial if there is to be hope of explaining the essential features of high energy physics data. The classification of superstring-inspired particle theories has yet to make detailed predictions but it has stimulated fruitful research in related problems of current interest in several other areas of physics and mathematics.

A fundamental problem of all present formulations of string theory is that they are based on an approximation scheme in which the geometry of the space and time through which the string is moving is treated nonquantum-mechanically and is an input to the theory. In a complete quantum theory of gravity space-time should emerge from the theory along with the particles and forces. Many exciting ideas are emerging in the search for an underlying principle that should lead to a reformulation of string theory that embodies this "quantum space-time." Such a principle is the holy grail of the subject.

For further reading, see reference 5.

1. **Green M B** *&* **Schwarz J H.** Supersymmetrical string theories. *Phys. Lett. B* 109:444-8. 1982. (Cited 205 times.)
2. **Alvarez-Gaume L** & **Witten** E. Gravitational anomalies. *Nucl. Phys. B* 234:269-330. 1983. (Cited 255 times.)
3. **Gross D J, Harvey J, Martinet E & Rohm R.** Heterotic string. *Phys. Rev. Lett.* 54:502-5, 1985. (Cited 880 times.)
4. **Candelas P, Horowitz G, Strominger A** *&* **Witten** E. Vacuum configurations for superstrings. *Nucl. Phys. B* 258:46-74. 1985. (Cited 1,170 times.)
5. **Green M B, Schwarz J H** *&* **Witten** E. *Superstring theory.* Cambridge, England: Cambridge University Press, 1987. 2 vols. (Cited 1,210 times.)