Heisenberg's remarkable discovery was that there are limits beyond which we cannot measure accurately, at the same time, the processes of nature. These limits are not imposed by the clumsy nature of our measuring devices or the extremely small size of the entities that we attempt to measure, but rather by the very way that nature presents itself to us. In other words, there exists an ambiguity barrier beyond which we never can pass without venturing into the realm of uncertainty. For this reason, Heisenberg's discovery became known as the "uncertainty principle".

The uncertainty principle reveals that as we penetrate deeper and deeper into the subatomic realm, we reach a certain point at which one part or another of our picture of nature becomes blurred, and there is no way to reclarify that part without blurring another part of the picture! It is as though we are adjusting a moving picture that is slightly out of focus. As we make the final adjustments, we are astonished to discover that when the right side of the picture clears, the left side of the picture becomes completely unfocused and nothing in it is recognizable. When we try to focus the left side of the picture, the right side starts to blur and soon the situation is reversed. If we try to strike a balance between these two extremes, both sides of the picture return to a recognizable condition, but in no way can we remove the original fuzziness from them.

The right side of the picture, in the original formulation of the uncertainty principle, corresponds to the position in space of a moving particle. The left side of the picture corresponds to its momentum. According to the uncertainty principle, we cannot measure accurately, at the same time, both the position and the momentum of a moving particle. The more precisely we determine one of these properties, the less we know about the other. If we precisely determine the position of the particle, then, strange as it sounds, there is nothing that we can know about its momentum. If we precisely determine the momentum of the particle, there is no way to determine its position.

To illustrate this strange statement, Heisenberg proposed that we imagine a super microscope of extraordinarily high resolving power – powerful enough, in fact, to be able to see an electron moving around in its orbit. Since electrons are so small, we cannot use ordinary light in our microscope because the wavelength of ordinary light is much too long to "see" electrons, in the same way that long sea waves barely are influenced by a thin pole sticking out of the water.

If we hold a strand of hair between a bright light and the wall, the hair casts no distinct shadow. It is so thin compared to the wavelengths of the light that the light waves bend around it instead of being obstructed by it. To see something, we have to obstruct the light waves we are looking with. In other words, to see something, we have to illuminate it with wavelengths smaller than it is. For this reason,

Heisenberg substituted gamma rays for visible light in his imaginary microscope. Gamma rays have the shortest wavelength known, which is just what we need for seeing an electron. An electron is large enough, compared to the tiny wavelength of gamma rays, to obstruct some of them: to make a shadow on the wall, as it were. This enables us to locate the electron.

The only problem, and this is where quantum physics enters the picture, is that, according to Planck's discovery, gamma rays, which have a much shorter wavelength than visible light, also contain much more energy than visible light. When a gamma ray strikes the imaginary electron, it illuminates the electron, but unfortunately, it also knocks it out of its orbit and changes its direction and speed (its momentum) in an unpredictable and uncontrollable way. (We cannot calculate precisely the angle of rebound between a particle, like the electron, and a wave, like the gamma ray). In short, if we use light with a wavelength short enough to locate the electron, we cause an undeterminable change in the electron's momentum.
The only alternative is to use a less energetic light. Less energetic light, however, causes our original problem: Light with an energy low enough not to disturb the momentum of the electron will have a wavelength so long that it will not be able to show us where the electron is! There is no way that we can know simultaneously the position and the momentum of a moving particle. All attempts to observe the electron alter the electron.

This is the primary significance of the uncertainty principle. At the subatomic level, we cannot observe something without changing it. There is no such thing as the independent observer who can stand on the sidelines watching nature run its course without influencing it. In one sense, this is not such a surprising statement. A good way to make a stranger turn and look at you is to stare intently at his back.

All of us know this, but we often discredit what we know when it contradicts what we have been taught is possible. Classical physics is based on the assumption that our reality, independently of us, runs its course in space and time according to strict causal laws. Not only can we observe it, unnoticed, as it unfolds, we can predict its future by applying causal laws to initial conditions. In this sense, Heisenberg's uncertainty principle is a very surprising statement.

We cannot apply Newton's laws of motion to an individual particle that does not have an initial location and momentum, which is exactly what the uncertainty principle shows us that we cannot determine. In other words, it is impossible, even in principle, ever to know enough about a particle in the subatomic realm to apply Newton's laws of motion which, for three centuries, were the basis of physics. *Newton's laws do not apply to the subatomic realm.**

*Strictly speaking, Newton's laws do not disappear totally in the subatomic **realm:** they remain valid as operator equations. Also, in some experiments involving subatomic particles Newton's laws may be taken as good approximations in the description of what is happening.

(Newton's *concepts* do not even apply in the subatomic realm.)
Given a beam of electrons, quantum theory can predict the probable distribution of the electrons over a given space at a given time, but quantum theory cannot predict, even in principle, the course of a single electron. The whole idea of a causal universe is undermined by the uncertainty principle.

In a related context, Niels Bohr wrote that quantum mechanics, by its essence, entails:

> . . . the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude toward the problem of physical reality.[9]

Yet there is another startling implication in the uncertainty principle. The concepts of position and momentum are intimately bound up with our idea of a thing called a moving particle. If, as it turns out, we cannot determine the position and momentum of a moving particle, as we always have assumed that we could, then we are forced to admit that this thing that we have been calling a moving particle, whatever it is, is not the "moving particle" we thought it was, because "moving particles" always have both position and momentum.

As Max Born put it:

> . . . if we can never actually determine more than one of the two properties (possession of a definite position and of a definite momentum), and if when one is determined we can make no assertion at all about the other property for the same moment, so far as our experiment goes, then we are not justified in concluding that the "thing" under examination can actually be described as a particle in the usual sense of the term"[10]

Whatever it is that we are observing can have a determinable momentum, and it can have a determinable position, but of these two properties, we must choose) for any given moment, which one we wish to bring into focus. This means, in reference to "moving particles" anyway, that we can never see them the way they "really are," but only the way we choose to see them!

As Heisenberg wrote:

> What we observe is not nature itself, but nature exposed to our method of questioning."[11]

The uncertainty principle rigorously brings us to the realization that there is no "My Way" which is separate from the world around us. It brings into question the very existence of an "objective" reality, as does complementarity and the concept of particles as correlations.

The tables have been turned. "The exact sciences" no longer study an objective reality that runs its course regardless of our interest in it or not, leaving us to fare as best we can while it goes its predetermined way. Science, at the level of subatomic events, is no longer "exact," the distinction between objective and subjective has vanished, and the portals through which the universe manifests itself are as we once knew a long time ago, those impotent, passive witnesses to its unfolding, the "I"s, of which we, insignificant we, are examples. The Cogs in the Machine have become the Creators of the Universe.

If the new physics has led us anywhere, it is back to ourselves, which, of course, is the only place that we could go.