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Workplace accidents and self-organized criticality

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HIGHLIGHTS

- Workplace accident data from the U.S. Bureau of Labor Statistics reveal a power-law relationship between the number of accidents and their severity.
- This universal power-law scaling suggests that workplace accidents are governed by self-organized criticality, implying a common underlying cause.
- Our results provide scientific support for the empirically proposed Heinrich accident triangle.

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ABSTRACT

The occurrence of workplace accidents is described within the context of self-organized criticality, a theory from statistical physics that governs a wide range of phenomena across physics, biology, geosciences, economics, and the social sciences. Workplace accident data from the U.S. Bureau of Labor Statistics reveal a power-law relationship between the number of accidents and their severity as measured by the number of days lost from work. This power-law scaling is indicative of workplace accidents being governed by self-organized criticality, suggesting that nearly all workplace accidents have a common underlying cause, independent of their severity. Such power-law scaling is found for all labor categories documented by the U.S. Bureau of Labor Statistics. Our results provide scientific support for the Heinrich accident triangle, with the practical implication that suppressing the rate of severe accidents requires changing the attitude toward workplace safety in general. By creating a culture that values safety, empowers individuals, and strives to continuously improve, accident rates can be suppressed across the full range of severities.

1. Introduction

Despite significant progress over the past several decades, the occurrence of workplace accidents remains an unfortunate reality [1], with over 900,000 lost-time accidents reported in the U.S. in 2015 alone [2]. Workplace accidents span the full range of severity from minor injuries such as cuts or scrapes to fatalities. Of course, minor incidents occur much more frequently than major ones. In order to understand the origin of the most serious accidents, we must consider the statistics of rare events, an important subject in statistical physics with a wide range of applications across a variety of disciplines.

One of the most successful physical theories to describe the statistics of rare events is that of self-organized criticality. Self-organized criticality was proposed by the late Danish physicist Per Bak in 1987 as a means for explaining how complex

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behavior in nature can arise from relatively simple origins [3–5]. Bak and coworkers originally proposed the concept of self-organized criticality to explain the distribution of avalanche sizes in a sandpile [3]. Bak considered a sandpile where individual grains are slowly sprinkled on top. Most of the time, the individual grains just add to the growing pile. However, sometimes a grain creates a large enough perturbation to generate a landslide. The size of the landslide can be measured by the number of grains of sand involved, and smaller landslides occur much more frequently than larger landslides. Of course, the occurrence of larger landslides will have a greater impact on the structure of the sandpile. Given their much lower frequency of occurrence, the study of the probability of these larger landslides is an example of the statistics of rare events, which is addressed directly by Bak's theory of self-organized criticality.

The concept of self-organized criticality has several important implications. First, it entails the natural emergence of a power-law distribution to describe the frequency of events as a function of size,

$$N(x) = ax^{-k}, \tag{1}$$

where N is the number of occurrences of an event of size x, a is a proportionality factor, and k is a scaling exponent. The power-law distribution gives a characteristic straight line when plotted on log–log axes, i.e., when plotting the logarithm of the number of occurrences versus the logarithm of the avalanche size, as

$$\log N = \log a - k \log x. \tag{2}$$

With such a log–log plot, the slope of the line reveals the value of the scaling exponent, k.

A second major insight from self-organized criticality is that all of the observed critical events have a common underlying origin, independent of their size. For the case of sandpiles, each landslide is caused by a perturbation induced by an individual falling grain of sand. The larger landslides occur much less frequently than the smaller landslides, but they all have the same fundamental cause. The term "self-organized" is used because the same scaling behavior emerges naturally, regardless of variation in the individual parameters of the experiment or the model.

Finally, a third major insight from self-organized criticality is its widespread applicability across a diverse range of fields, including physics, geology, materials science, biology, mathematics, economics, and even sociology [6,7]. An archetypal example from geology is the statistics of earthquake magnitudes [8]. All earthquakes have the same fundamental origin, i.e., a rock breaking along a fault line, which generates seismic waves. Low-magnitude earthquakes occur frequently, although we usually do not notice since they are too small to be felt. The earthquakes of greater concern are the more rarely occurring high-magnitude earthquakes that can create massive damage and loss of human life. The probability of these high-magnitude earthquakes occurring is another example of the statistics of rare events. Since all earthquakes have the same underlying origin, the frequency of earthquakes of varying magnitude follows a power-law distribution, the same distribution that describes the statistics of landslides in Bak's study of sandpiles. In this manner, both landslides and earthquakes are examples of self-organized criticality.

Other examples of phenomena described by self-organized criticality include forest fires, river flows, climatology, disease epidemics, financial markets, and social networks [6,7]. Self-organized criticality also describes the evolution of complex proteins in the field of biology [9,10]. Within materials science, self-organized criticality explains the existence of optimized stress-free glasses that exhibit a minimum in aging behavior [11]. In the social and economic sciences, self-organized criticality explains the probability distributions of wars and stock market crashes [6].

Here we propose that workplace accidents are another example of self-organized criticality. Workplace accident data from the U.S. Bureau of Labor Statistics reveal a power-law distribution of accident rates as a function of the number of days lost from work, a quantitative measure of the severity of an accident. As a characteristic feature of self-organized criticality, this power-law scaling points to a common underlying cause of workplace accidents, independent of their severity and the particular labor category in which they occur. We propose that the most effective means of reducing the rate of severe accidents in the workplace is to reduce the accident rate overall by creating a culture that incorporates safety as one of its core values. This result is consistent with the approach advocated by Heinrich [12] and provides a scientific basis for Heinrich's empirically derived accident triangle.

2. Methods

The data are obtained from the U.S. Bureau of Labor Statistics (U.S. Department of Labor), gathered through the Survey of Occupational Injuries and Illnesses in cooperation with participating state agencies. Here we consider the distribution of nonfatal injuries resulting in at least one day lost from work. Table 1 provides the raw data used for our study [2] for 28 different labor categories. The first row is the combined set of data for all private industry in the U.S.

The power-law distribution of Eq. (1) is independently fit to each row of data in Table 1 to determine the optimized values of a and k using a least squares method. For the columns in Table 1 where the reported data are binned across multiple days, we consider an average number of accidents at the midpoint of the reported range of days. The final column of data for 31 or more lost days of work is not used for curve fitting, since the upper bound of the number of days is unknown and a midpoint cannot be determined. The quality of the power-law fits is quantified by the standard coefficient of determination, R^2. The optimized parameters, a and k, and the R^2 values for each labor category are provided in Table 2.