CALIFORNIA ON FIRE
AN ILLUSTRATION OF SELF-ORGANIZED CRITICALITY

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California holds the dubious record for the most natural disasters among all states of the Union. Earthquakes and forest fires are the predominant hazards, costing billions of dollars per year.

In this module, we study the largest of California’s recent forest fires – called wild fires by Californians – and show that the exceedence probability for California wildfires obeyed a power law in 2007. Thus, wildfires are high-risk hazards that should be prevented by changes in policy.

Next, a simple model of forest fires is proposed and computer simulated so that we can understand what determines risk and resilience in complex systems such as forests and other infrastructure systems. This simulation illustrates a key concept in the scientific study of critical infrastructure protection: self-organized criticality. S. O. C. is a fundamental principle of risk and explains why some infrastructure is more resilient than others. It also divides various kinds of hazards into two classes: low- and high-risk.

SOC is manifest in almost all critical infrastructure systems, typically due to percolation – the process of increasing density of trees, in this case. Percolation occurs in different ways in different infrastructures. We will generalize the concept of percolation and self-organized criticality in subsequent lessons. But now, let us turn our attention to one of the worst hazards facing Californians every year.
California Wildfires

During most of the year California's moderate climate is determined by Pacific Ocean winds that cool the state during the summer. But during the months of September and October, winds reverse themselves, flowing from the Sierra Mountains out to sea. These are called Santa Ana Winds, and they raise the temperature as they flow from East to West. Santa Ana winds make October the warmest month of the year. And, in some years, temperatures in Southern California rise to triple digits.

Careless campers, arsonists, and accidents cause many fires that are quickly extinguished, but once in a while, these fires explode, spreading like, well, er, wildfire, from the mountains to the Ocean. Californians love the outdoors, and many houses are adjacent to forests, which produces inevitable casualties. The October 2007 wildfires were no exception. During the period spanning late October and early November, 17 Californians lost their lives, and 140 were injured due to a massive set of fires across the lower half of the state. Three thousand homes were destroyed before the flames were brought under control.

The October 2007 wildfires displaced nearly one million people, burned over half a million acres, and destroyed or disabled portions of the power grid and the telephone system, and damaged water resources. Recall that much of the drinking water in southern California comes from the mountainous area where forests catch on fire and burn everything in sight. Therefore, California wildfires affect several critical infrastructure sectors.

California Wildfires - Consequences

The Santa Ana fires are so big they can easily be viewed from space. Here you see a satellite photo of the October fires. These wildfires ignited large portions of forests from North to South. They created eerie black and gray clouds blanking out the sun, and turning daytime into a “nuclear winter”. Note in this photo from space, the direction of the plume: from East to West.

The U.S. Forest Service, under the Department of Interior must respond to these disasters. This is a huge undertaking. At their peak, the October fires consumed more than 500,000 acres, required 1500 fire engines to combat, and deployed over 13,000 fire fighters. These numbers are too big for one state to handle, so the Forest Service relied heavily on firefighters from Washington, Oregon, Idaho, Nevada, and Arizona. Response is a regional affair, marshalling people and equipment from all over the West Coast. The consequences
are huge in terms of both resources consumed and damages to the forests, water supply, and people's homes.

SLIDE 6

California Wildfires - Risk

How bad are these fires? How often do they occur? Are California wildfires high- or low-risk hazards? These questions are answered by analyzing historical data provided by the U.S. Forest Service.

Exceedence probability is the probability that a fire consumes so-many acres OR MORE, each time a fire breaks out. In other words, it ranks forest fires according to the fraction of all fires that exceed a certain size. Exceedence probability is simple to compute: merely count the number of fires of a certain size OR MORE, and normalize the counts so they sum to 100%. Doing this with the data provided by the U.S. Forest Service provides the black dots in this chart. The red line is a power law that best fits the black dots.

The red line is a power law with exponent equal to 0.6, which places this hazard in the high-risk category. That is, risk increases with increasing size of the forest fire, as shown here by a dotted white line. California wildfires are high-risk, which suggests a strategy of prevention. But first, we need to understand why California forests are so vulnerable to widespread conflagration even when they start out as very small fires.
I am using PML Risk, or probable maximum loss as my metric of risk. Recall that PML Risk is the product of exceedence probability times consequence. PML Risk is computed by multiplying the vertical axis by the horizontal axis of this chart.

Why are these forests high risk?

SLIDE 7

Forest Fire Percolation I

Risk of high consequence forest fires is determined by the density of the forest: the more dense, the more likely consequences will be high. Thus, a forest becomes less resilient as density increases. Density, on the other hand, increases as a forest gets older. Forests age and become more likely to burn down as they become denser.

This phenomenon is illustrated by the following simulation. Imagine a square forest as shown here. Trees are planted at random, as shown by green squares within the larger square forest. Occasionally, Zeus casts a random bolt of lightening into the forest. If the bolt hits a tree – or a green square as shown here – it catches on fire, and burns down. In addition, all trees immediately adjacent to a burning tree are also burned down. The forest
Fire spreads until there are no other trees adjacent to a burning tree. Bolts are cast into the forest at constant intervals. In this case, we cast a bolt of lightning once every 25 time steps.

Initially, bolts of lightning miss: they do not hit a tree, because trees are rare. Over time random planting of trees increases tree density so the probability of a fire increases. This increase is inevitable as tree density increases, but keep in mind that the size of the forest fire is determined by the size of tree clusters. That is, big fires are the result of hitting a tree within a big cluster of trees, and small fires are the result of hitting a small cluster. Clusters are a form of percolation: the longer we go without a fire, the larger the percolated clusters, and hence when a fire does occur, it is more likely to be large.

This is confirmed by increasing the interval between bolts of lightning, shown next.

**Slide 8**

**Forest Fire Percolation II**

Here we show the same simulation except for one difference: the interval between bolts of lightning is four times longer. Zeus casts a bolt of lightning once every 100 time steps instead of once every 25 time steps. Note the change in the exceedence probability curve, and hence the resilience exponent. Resilience is almost one-half as much when interval time is four times as much. Frequent fires produce a resilience of 0.53, while infrequent forest fires produce a lower resilience of 0.31. In other words, it is **better** to incur frequent fires than infrequent fires!

Why is this counter intuitive? Normally we would expect fewer fires to produce a better outcome. Instead, frequent fires produce a better result, in terms of risk. The explanation is simple: less percolation means less risk. That is, infrequent forest fires lead to greater percolation, which leads to greater consequence, which leads to greater risk. In a way, it is better to have frequent fires, because they thin out the forest.

Forest fire simulations illustrate a fundamental concept of infrastructure protection: self-organized criticality, or SOC. Increasing SOC is identical to increasing risk. The more self-organized a system is, the more risk is involved. In general, we want to reduce SOC. In this case, we can reduce SOC by reducing percolation. That is, by thinning the forest.

**Slide 9**

**Forest Self-Organized Criticality**

SOC equals risk. In fact, we can show by simulation that risk increases with SOC, which increases according to the strike interval as shown in this chart. Recall that strike interval is a measure of lightning strike infrequency. The larger the interval, the less frequent the
bolts of lightning. Thus, consequences increase with decrease in frequency of lightning strikes.

In this simulation, consequences increase as the square root of interval, but this is an artifact of the simulation. The forest is contained within a square, and the clusters were squares. Clusters grow linearly with time, but the dimension of each cluster grows as the square root of time. Hence, the square root result shown here.

This plot shows that consequence increases with strike interval, which increases percolation, which increases SOC, which increases risk. Consequence, Percolation, SOC, and risk are all different terms for the same phenomenon.

Slide 10

Generalization: Self-Organized Criticality

So now we have an elementary theory of catastrophes and risk. We see that random incidents play a big role in resilience, and resilience is tied to risk. However, resilience is a property of a system, not merely a single asset within a system. The vulnerability of a tree in our simulated forest is very low, but the resiliency of the entire forest depends on percolation – many trees. Here is the big idea: SOC explains why resilience differs for different critical infrastructure systems. SOC explains why “100-year floods” occur more often than every 100 years. SOC explains why some systems are more resilient than others, and in special cases, it identifies the reason why power grids, forests, telecommunication systems, and transportation systems are not particularly resilient.

Josh Ramo has even applied SOC to the political and social sectors, explaining why we live in the Age of the Unthinkable.

Here is your take away: critical infrastructure systems can be made more resilient by reducing their self-organized criticality.

Slide 11

Per Bak’s Sand Pile Experiment

SOC is not a new idea. In fact it was coined in 1987 by Per Bak an eccentric physicist who was inspired by colleagues at the Sante Fe Institute. The seminal experiment by Bak, Tang, and Weisenfeld that describes self-organized criticality was subsequently called the “BTW experiment” by the scientific community. Bak and associates proposed a simple sand pile experiment as follows:
Consider a pile of sand built up over time by simply dropping grains of sand onto a pile. At first the sand pile simply builds up into a cone shape, as shown here. Grains continue to pile up until at some point avalanches begin to occur. These avalanches are of various sizes and they appear to occur at random. At least, Bak was unable to predict when an avalanche might occur.

Per Bak could not predict the timing or size of avalanches but he showed that the exceedence probability of avalanches obeys a power law just like the exceedence probability of our forest fires! Interestingly, many catastrophes obey power laws and the BTW experiment is no different. In fact, the BTW experiment, or sand pile experiment, has become the canonical catastrophe. Most other disasters are modeled by this simple sand pile.

Recall that power laws are fractals – they are self-similar. This suggests that big accidents are simply large replicas of small accidents. Big catastrophes are magnified small catastrophes. Per Bak called this “punctuated equilibrium”, and Perrow called these “normal accidents”. Catastrophes are both punctuated and accidental, but we now know that randomness and self-organized criticality plays a big role in cause and effect. Catastrophes are made larger and more likely by SOC.

**Slide 12**

Self-Organized Criticality

The concept of self-organized criticality is widespread. Turcotte used it to explain earthquakes, floods, and other hazards. It appears that percolation, self-organized criticality, and normal accidents are all different facets of the same thing. In summary, this theory explains many natural hazards and how they lead to disaster. Nearly all systems in nature and the human-made world of infrastructure start out as stable systems. The Interstate Highway system was initially stable, because density of automobiles takes time to build up, until today’s freeways are critical. Power grids were initially stable, but over time they become more and more self-organized, same thing for forests, telecommunications systems, and hospital systems.

As these systems become self-organized they also approach a tipping point called the critical point. Once the critical point is reached, it takes only a very minor “accident” to push the system over the top, which leads to a sudden drop or correction. The financial system collapse of 2008 is a dramatic recent example.

Before a system reaches its critical point it may suffer from a number of normal accidents or corrections, but these have little impact because the system is not critical. But once a system reaches its critical point, even the smallest perturbation can have major
consequences. As a system becomes more critical its eventual collapse becomes greater. Catastrophe is magnified, and inevitable.

**Slide 13**

Exceedence Probability and Hazards I

Natural hazards produce consequences that vary in size and frequency, but they have one thing in common: their exceedence probability curves are power laws! This is an amazing result, because hazards are very different from one another. And yet, we can understand them in terms of our exceedence probability curves, catastrophe theory, and self-organization. Our critical infrastructure systems’ resiliency varies because they are in different states of self-organization.

Low-risk hazards are defined as hazards that historically produce a high exceedence probability exponent, q. If q is greater than one, then risk diminishes as consequence increases. In fact, high-consequence incidents are so rare that their risk contributions practically vanish.

Note that terrorism is a low-risk hazard. The financial sector as defined by the S&P 500 is low risk. Earthquakes, asteroids, and Pacific hurricanes are on the border between high- and low-risk hazards.

The exceedence probability exponent q is a measure of resilience. Large values of q imply high resilience. Low values of q imply low resilience. Therefore, we will define q as our measure of resilience. Systems with large values of q are resilient. Otherwise, they are not.

**Slide 14**

Exceedence Probability and Hazards II

In this table we see that a number of well-known hazards are high risk because they produce consequences with a resilient exponent q less than one. In other words, risk increases with increases in consequence. High consequence incidents are more likely for these hazards, which results in higher risk.

Even though the measures of consequence may differ as shown here, these hazards obey a power law. Note that diseases are among the highest risk hazards we know of. (The public telephone system data was collected in the 1990s. All other data is much more robust, some going back in time for centuries.)

What does this mean?
Slide 15

Causes of Self-Organized Criticality

We have shown how percolation of trees in a forest leads to high risk and low resilience. The forest fire simulation illustrates site percolation – the increase of cluster size around a certain site in the forest.

Another type of percolation is known as bond percolation. In more complex systems bonds are established by linkages. Here we show the linkages as links in a network. Bond percolation in a network is equivalent to increases in density of links. That is, increasing link density is a form of SOC.

Networks suffer from site percolation when hubs form or one node or link becomes the dominant betweenness node or link. Too many links or too many paths passing through a node or link are not good for resiliency. The presence of high degree nodes, or high betweenness nodes or links is a form of percolation leading to SOC.

Percolation theory explains two forms of SOC. It also suggests policy options.

Slide 16

Policy Implications

The implications for policy are obvious: Catastrophes are caused by a combination of randomness, self-organized criticality, and the structure of complex adaptive systems.

Consequences are magnified by SOC.
Risk is increased by SOC
SOC is increased by various forms of percolation.
These are the elements of catastrophe.

A number of remedies are available, but none are very desirable. We can back away from self-organized criticality by running systems such as the electric power grid at a level far below optimal performance, but this produces lower profits and less efficiency. In fact, Per Bak claims that nature tends to organize systems to the brink of disaster simply because the critical point is also the optimal point. If we want to optimize performance, we are doomed to drive systems to their critical points.

We can add standby surge capacity to hospitals, transportation systems, communication systems, etc., but of course, this increases cost.
Applying network theory to these systems, we can decrease their connectivity by reducing the density of links. We can reduce or eliminate hubs and provide alternative paths through networks to reduce betweeness.

Finally, we can live with self-organized criticality by simply hardening the hubs and betweeners. That is, we can guarantee survivability of critical nodes and links by protecting them, duplicating them, or somehow reducing their vulnerability to a variety of natural and human-made hazards. Again, this costs money, and may decrease profits.

**Slide 17**

Further Reading

The interested viewer can learn more by reading my *Homeland Security Affairs* article on self-organized criticality published in January 2010 at [www.hsaj.org](http://www.hsaj.org). This article surveys the principles described here, and explains the Amaral-Meyer network, the forest fires simulation, and low- and high-risk hazards. It suggests a dual strategy of preventing high-risk hazards and responding to low-risk hazards.

The 4-volume series edited by John Voeller contains my paper on telecommunications. The paper appears in volume 4, and describes how the telecommunications sector of the United States has evolved into a state of self-organized criticality over the past 100 years. Telecommunications, as it turns out, is critical because of site percolation: too many links connect too few communication hubs to the system. If we want to improve resilience, these critical hubs must be either eliminated or hardened.

Google the phrase “self-organized criticality” and you will get thousands of papers on the subject. SOC is a property of many physical systems and grew out of complexity theory. And we now know that complexity theory explains many things!

**Slide 26**

Closing Credits

Music