Tragedy struck the small village of Aussios in the French Alps on February 14, 2005, when a huge hard-slab avalanche caught and fatally wounded a well known, respected mountain worker. Pompon, a local IFMGA-certified mountain guide and ski patroller with about 20 years of professional avalanche experience, triggered the fatal avalanche in a wide bowl called Les Balmes. The upper section of the 300-meter-wide bowl is divided into several separate gullies or talus slopes which can normally be controlled individually with hand charges from above. Apparently intending to view the negative results of the first shot placement on his familiar control route, or perhaps to test the snow's resistance, Pompon slid slightly out onto a convex slope measuring less than 30 degrees on the upper fringes of the second gully. Strong winds the day before had loaded Les Balmes with a significant amount of snow, and the avalanche Pompon triggered was much bigger than expected. His partner watched the quasi-simultaneous release of the entire bowl as the massive avalanche carried Pompon more than 600 vertical meters and mortally wounded him. He died a few months later after suffering a deep coma.

This casualty tragically illustrates how an avalanche specialist, with a perfect knowledge of the field, might eventually be trapped by a larger-than-expected slab-avalanche release. Both rupture mechanics and statistical physics can bring new insight into this problem. These theoretical approaches perfectly fit field observations. They explain why some unexpected avalanches may release and also, more commonly, why nothing happens even when most conditions for triggering seem to be met.

A few basic concepts
Avalanche-release phenomena may be classified into two main categories: spontaneous and artificially triggered ones. Spontaneous failures are of a ductile nature. They result from a strain rate increase during snow creep or reptation, up to a critical point at which failure suddenly occurs. We shall focus here on accidental and artificial avalanches. Such failures occur within a much shorter time scale, correspond to a rapid change in the controlling parameters, and are of a brittle nature. Any physical evolution process needs a driving force, which may or not be balanced by a resistance. In order to understand the phenomenon, we need to identify both the driving force and the resistance.

• Driving force:
A process is likely to occur spontaneously if it contributes to a decrease in the energy of the system down to a stable state. In the avalanche problem, the available-energy stems from the snow weight. The weight of a skier (some 80 kg) is extremely small as compared to the weight of the snow involved in the avalanche-triggering mechanism (several millions of kg).

• Resistance:
The reason why the snow cover remains on mountain slopes is snow cohesion, which provides resistance to rupture. This is not the case for water, which would immediately flow downslope as it has no cohesion. Snow cohesion attributes in keeping the snow cover in a metastable state. Two types of resistance have to be overcome in order to release an avalanche: i) the shear resistance of the bonding between the slab and the older snow substrate, known as weak layer, and ii) the rupture stress of the cohesive slab. The local action of a skier may gradually damage the weak layer, which is more similar to a brittle house of cards than to ball bearings. It may also contribute to opening a crown crack across the slab thickness. Therefore, the skier's action only deals with possible changes in the resistance of the weak layer or of the slab and not with the driving force.

A simple sketch of the system
In the case of accidental or of artificial triggering, both the cohesive slab and the weak layer behave as elastic/brittle bodies, they may deform elastically under stress and fail in a brittle way if the stress exceeds a threshold value. The elastic/brittle slab is represented in the above diagram as a series of blocks linked by elastic/brittle springs lying on a collapsible house of cards; (b) the skier's load may collapse part of the house of cards (basal crack); (c) driven by either the skier's action or the snow weight, the basal crack may extend; (d) when the extension of the basal crack is large enough, the weight of the hanging part of the slab initiates a crown crack at the top, resulting usually in the avalanche release.

A combination of four steps in series
We propose that accidental or artificial avalanche release stems from four mechanisms:
1. collapse of the weak layer that results in the nucleation of a basal crack,
2. propagation or expansion of the basal crack
3. opening of the crown crack at the upper rim of the basal crack
4. expansion of the crown crack, which leads to the avalanche release.
These mechanisms operate in series; if any single one does not occur, the avalanche is not released.

Figure 1: (a) A slab on a weak layer may be seen as a series of blocks linked by elastic/brittle springs lying on a collapsible house of cards; (b) the skier's load may collapse part of the house of cards (basal crack); (c) driven by either the skier's action or the snow weight, the basal crack may extend; (d) when the extension of the basal crack is large enough, the weight of the hanging part of the slab initiates a crown crack at the top, resulting usually in the avalanche release.
SLAB TRIGGERING continued from previous page

at the top of the basal crack when the tensile stress in the slab reaches a threshold value. Since different basal crack growth mechanisms can operate, we expect two different types of avalanche triggering to occur (below).

Subcritical triggering:
In this case, the basal crack gradually extends step by step in an area around the skier’s path. At some stage of this extension, the tensile stress experienced by the slab at the upper rim may exceed the slab rupture stress. The slab is thus limited to the area actually damaged by the skier, who is likely to be located at the boundary of this zone when the avalanche is released. This scenario might happen when the slab cohesion is low. A small-size basal crack is sufficient to reach the slab tensile rupture stress. The cut made by the skis in the soft slab may also help the slab failure along the skier’s path. By contrast, with stronger slabs, the slab-rupture stress may not be reached, the crown crack does not open, and the skier gets out of the hazardous area without triggering the avalanche.

Supercritical triggering:
Now the slab is significantly stronger (i.e., crown crack opening becomes more difficult), and/or the driving force for basal-crack expansion is larger (i.e., the slab is heavier). The basal-crack size may reach the critical value for spontaneous expansion before a crown crack can open. At this point, the basal crack starts expanding with a significantly larger velocity. Crown-crack opening occurs a short time later, often at quite a large distance from the skier, when the weight of the freed part of the slab has become large enough to trigger the failure of the tough slab. The starting zone is much bigger than in the previous case, and the skier is trapped somewhere in the middle of it. In some conditions, it may result in a “bang” at slab failure. A simple calculation (Louchet 2001) shows that supercritical triggering is favored by large slab weights and that conditions for its occurrence are more readily met on slopes around a universal angle of 35˚.

4. Crown crack expansion and avalanche release
With some modifications, Griffith’s criterion may also apply to the crown crack. If the tensile load is large enough to nucleate an incipient crown crack, it will become large enough to trigger, as the increasing crack size requires a decreasing propagation stress. The crown crack grows very rapidly (brittle failure), until the stress concentration at its tips reaches the shear-failure stress on both sides. The bottom rim usually fails first but when this stage as the whole slab weight is now transferred to it, and the avalanche is released. In most cases, the nucleation of the crown crack is immediately followed by its expansion and by the avalanche release.

For the weak layer, the slab rupture threshold may have scattered values. An incipient crown crack usually appears at one of the weakest places. Its subsequent propagation may meet a tougher zone, which may hinder its growth. In this case, the basal crack goes on extending up further. We often observe stable incipient crown cracks.

III) The theory explains avalanches which are released...and those which are not
In this section, we discuss several field situations and examples of avalanche release from real life, in the light of the four basic steps developed above. We show in these examples that the conditions for avalanche release require that all four conditions be fulfilled. If even one of them is not, the avalanche will not be triggered.

Are huge snow accumulations favorable or unfavorable for avalanche release?
A thick snow cover may favor basal-crack expansion. This is true for natural, artificial, or accidental triggerings. But basal-crack nucleation by a skier or by explosives is impossible if the involved slab is too thick, due to poor pressure transmission to the weak layer. This is probably why accidental releases are more frequent during early winter: weak layers are readily formed during this period and frequently covered with shallow basal slabs. Crown cracks are therefore more likely to be nucleated.

Avalanche professionals sometimes deplore the poor efficiency of artificial triggerings in spite of huge snow accumulations. Often the snow depth is probably too large to allow artificial triggering, and not large enough to drive a natural avalanche release.

Why should skiers cross a hazardous area one after the other rather than in groups?
This recommendation is supported by at least two reasons. The first reason is that if an avalanche catches one of them, the others might successfully conduct a rescue. The second reason is based on a situation where the weight of a single skier is insufficient to nucleate a basal crack, like on a thick slab, but the combined weight of several skiers crossing the area simultaneously may be large enough to nucleate it.

On shallower slabs, a single skier may nucleate a basal crack (step 1), but not on it on a limited area (step 2), and get out from the hazardous zone without triggering an avalanche. In this case, crown-crack nucleation (step 3), could not occur because the hung part of the slab was too small or not heavy enough to open the crown crack. If a second skier, then a third one, and so on, cross the same zone along slightly different paths, the corresponding basal cracks may merge, resulting in a unique crack that may be large enough to either directly open a crown crack (step 3, subcritical mode) or expand it in an unstable way before opening a large crown crack far above (step 3, supercritical mode). The resulting triggering would not depend on whether skiers have crossed the zone together or one after the other. A reasonable recommendation to minimize the risk might be to cross the dangerous area successively and along the same path, although by doing this, the skiers could disturb the weak layer due to deeper penetration of the slab by the successive skiers.

Why are most avalanches observed on slopes around 35˚?
There is a general agreement that the most favorable slopes for avalanche triggering are around 35˚. This observation may be explained using the above considerations. A limited basal crack width (as in Figures 3a or b) that remains smaller than the critical size for spontaneous expansion (step 2, subcritical mode), may result either in a limited starting zone or in no triggering at all. By contrast, if the basal crack is wide enough (or the critical size small enough), the resulting spontaneous expansion cannot be stopped (step 2, supercritical mode) until stratigraphy changes. Indeed, the tensile stress experienced by the slab at the upper crack tip continuously increases until the slab-basal rupture stress is reached, and the crown crack opens (step 3). The avalanche is more likely to be released at this stage, as compared to the case of a limited subcritical growth (step 4).

As the supercritical scenario is favored for slopes around 35˚, avalanches are expected to be preferentially triggered on such slopes and not around the classical 45˚ expected from simple mechanical arguments. This particular observed feature is a strong argument in favor of our present approach.

Why are tough slabs often associated with large avalanches?
The tougher the slab, the more difficult crown-crack nucleation is. This is probably why tough-slab avalanches are usually big. The amount of elastic energy stored in such big slides can only push a crown crack open before crown-crack expansion may result in an impressive “bang.”

Why do crown cracks often open at outcrops or trees?
It is frequently observed that the crown crack starts opening (step 3) at an outcrop or a tree even on a ski or surf track. These features act as weak points in the slab, which help crown-crack nucleation. The same mechanism takes place at convexities. Such weak points play a dual role: they facilitate slab triggering through crown crack nucleation, but they prevent large-scale propagation of basal cracks, which may have resulted in the release of very large slabs. In other words, large slab avalanches are likely to be found on wide and smooth slopes without weak points or field heterogeneities like trees, sparse rocks, or outcrops.

Why are some avalanches triggered on flat ground?
The propagation of the basal crack (step 2) helps us to understand accidents occurring on gentle slopes, neighbored by slopes steeper than the fateful 30˚. The victims are responsible for the nucleation of the basal crack, which may gradually expand to the steeper slopes. At this point, the driving force is more efficient, and the basal crack may become unstable and propagate rapidly in the supercritical mode, triggering one or several slabs.

Why do “whumphs” on steep slopes not necessarily result in avalanche release?
Sometimes a whumph is clearly felt on a rather steep slope (step 1), but without any further consequence. This case may correspond to a weak layer of small dimensions (blown out by the wind as it still was at the surface or swept out by a previous avalanche), at the boundaries of which the basal crack propagation stops (step 2) before reaching the size necessary for unstable propagation or for directly opening a crown crack (step 3) and releasing the avalanche (step 4).

IV) Snow cover variability and triggering scenarios:
The different triggering scenarios therefore depend on the spatio-temporal variability of the snow mechanical properties, which are involved during the four successive steps of the triggering process. The snow cover is most often heterogeneous in thickness and/or mechanical resistance. For this reason, the type of basal crack left along the skier’s path may vary: for example from the case of Figure 3a to that of Figure 3b, or worse, that of Figure 3c. This may be the case for instance if snow evolves from fluffy to stiff. Another example is that of an artificial crack growth under a shallow slab (Figure 3b) that can quickly turn to the case of Figure 3c if the slab thickness becomes locally larger. This scenario is especially threatening for experienced mountaineers, who usually pay close attention to the snow condition under their skis but are less aware of the danger due to the snow variability in the neighborhood. In both cases, a slope that seems to be quite safe may suddenly be swept out by a spanning avalanche.

Experienced skiers sometimes succeed in triggering slab avalanches without being caught in them. It may happen indeed that a skier triggers an avalanche of limited size. Most of the time, this is a subcritical triggering. The tensile crack (a) develops on the slab resulting

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from the collapse of the weak layer on a limited area is large enough to open a crown crack just above. The avalanche is released, but the skier can escape if he can control his or her trajectory. This is likely to occur with weak and shallow slabs made of loose snow.

Slope cutting usually works, but not always. This could be the reason why Pompon was caught while trying to trigger an avalanche near Chamonix. A slab avalanche may occasionally largely exceed the usual size most often seen on a particular slope. This is the nature of a supercritical triggering. The collapsed part of the weak layer rapidly extends in all directions. The crown crack may open far above the skier, who gets trapped in the middle of a huge triggered slab that may reach widths up to several hundred meters. Escape is impossible, and the outcome is usually fatal. This scenario is more likely to take place when a slab is composed of tough and heavy snow. Being aware of the existence of these two fracturing modes is fundamental for practitioners, as predicting which one of these two is likely to occur is risky, even if the supercritical mode is favored by the presence of a weak layer, a heavy, thick, and tough upper snow layer, and slopes angles around 35°.

The layout procedure for triggering devices, like gas exploders, should also take into account these two different possibilities: the separation between two neighbor devices is different depending on whether sub or supercritical avalanches need to be triggered. Frequent subcritical triggering usually probably hinders the release of large slabs, whereas optimizing supercritical triggerings may lead to unexpected consequences, owing to the uncontrolled size of the avalanche.

V) From a basic understanding towards a possible prediction?

Despite the large variety of observed avalanche phenomena, their understanding requires at least four different models, but may be described by using a few simple concepts. Too simple of an approach, based on a balance between a global snow stress and a supposed overloading due to the skier, would not be able to describe the variety of observed triggerings. By contrast, such a variety of behaviors can be easily accounted for on the basis of the four-step scenario described above.

The final result in terms of avalanche occurrence and size may vary drastically, depending on the way in which these processes are connected. Human action appears to be connected to local and global change in the weak layer resistance, which may nevertheless lead to quite different scenarios depending on the local and global snow cover properties. The snow cover is such a complex system, with such a large spatio-temporal variability, that a deterministic prediction of avalanche release turns out to be impossible. It would require: 1) a method of measuring snow properties all day long, and a slight uncertainty in these measurements might lead to totally different behaviors. Our ignorance can be dealt with in terms of randomness. Field measurements show that starting zones obey a specific size distribution, taking the mathematical form of a power law, also known as a “scale invariant” distribution. This means that there are many small avalanches and a few big ones. But the ratio between the number of avalanches of different sizes is perfectly well defined, and there is no characteristic avalanche size. We demonstrated using cellular automata simulations (Failliettaz et al. 2004) that such scale invariance can be reproduced, provided random values are used for rupture thresholds. The consequences are twofold:

- Scale invariant size distributions obtained from field measurements are a signature of the randomness and foresight of many men and women, whose collective work is mandated to become inert within a short time period, drives the total shot size to the 400-450 psi max pressures of the current LOCAT unexpectedly.

- The higher pressure not only allows greater range, but also the ability to place several pounds of explosives in the field, thus doubling the amount of energy.

In addition to its pricy gun cost, the French Launcher charges $170 for its shells. The French Launcher shoots an 88 mm projectile at high speeds, up to 2,500 feet per second, and boasts a range of up to 3,500 feet.

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