Maths, Physics & Chem

Network resuscitation – pumping life into a failed complex system

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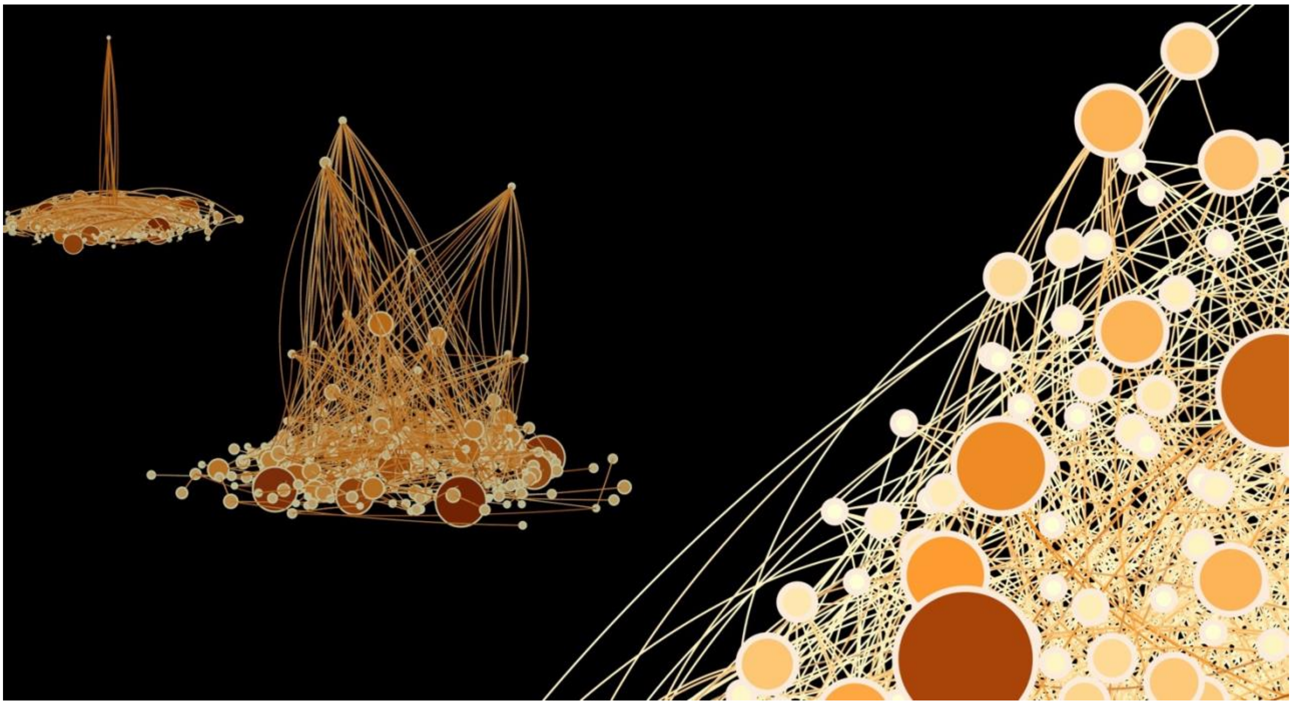
ABSTRACT

When a complex social, biological or ecological network collapses, we seek to steer it back towards functionality. Our recent work maps unique conditions - the recoverable phase - when this can be achieved by controlling just one component. With applications from neuronal networks to our gut-microbiome, we show how a single intervention point can reignite the entire system's functionality.



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We have seen this many times in movies: an unconscious protagonist is jolted back to life through abrupt electrical shocks from a defibrillator. But how is that possible? A functioning body is, after all, an intricate machinery of extremely complex organs, all having to perform their tasks in a perfectly coordinated fashion. How then, can you spark life into something so complex by such a simple and crude intervention?

This question, it turns out, finds parallels in many natural systems around us. Consider, for example, an eco-system of multiple interacting species. Under natural conditions the network thrives, all species are abundant, and the system is functional. Environmental perturbations, however, such as species extinction, pollution, or resource depletion, disrupt the state of the system, and – if strong enough – may lead to a sudden collapse, as the eco-system transitions to a dysfunctional state. When this happens, we seek precisely the system's *defibrillator* – a way to jolt it back to functionality.

The naive approach is to reverse the damage: reintroduce the extinct species, clean up the pollutants or retrieve the scarce resources. This, however, is often insufficient. The reason is a phenomenon called *hysteresis*. It describes a state in which the transitions prefer one direction over the other. For example, a polluted reservoir may undergo an ecological collapse. Depolluting it, while the right thing to do, will not guarantee its spontaneous recovery. In a similar fashion, if you knock out genes from a cell, at a certain point, extracting one gene too many, the cell will die. But retrieving the lost genes will not bring the cell back to life. Hence, hysteresis captures a ratchet-like motion, in which transitions are easy in one direction, but difficult, or even impossible, in the reverse.

As a consequence, to revive a failed system, we must not only retrieve the previous, pre-failure, conditions, but also *reignite* the *dynamics* of the system, *i.e.* drive it back towards functionality. But how would you achieve that? Recalling our failed eco-system, it seems that after you reverse the damage, *e.g.*, depollute it, you would need to recover the lost population of every single one of its now diluted species. Hence, one by one, you drive the system back to its functional state. The challenge is that, whether it is an ecological network, a living cell or our brain networks, we rarely possess this level of control over all network components.

To address this, we used mathematical modelling to uncovera new dynamic state of complex networked systems – the *recoverable* phase. In this state, the network components interact strongly enough, such that we can push the network back to functionality by controlling just one single component. For example, you can revive a failed eco-system by boosting the population of a selected species s. This species will then impact its interacting partners, whose abundance depends on the availability of s. s will then boost their neighbors, and eventually, a recovery wave will sweep through the network, pushing it back into the desired functional state. Similarly, one can excite a single neuron to drive an entire neuronal network into activity, or, as demonstrate in our analysis, revive a damaged cell by activating one gene.

As a concrete example we focused on a unique ecological system, the gut-microbiome, where hundreds of microbial species, residing within our bowels, interact through a complex network of cooperative and opposing links. This system, crucial for our well-being, is often damaged due to excessive antibiotic treatment. The microbes dwindle in abundance, and, as a result, many of our bodily functions are disrupted. Injecting back all the missing microbial species is, of course, not possible. However, we have shown that under the right conditions, we can identify a set of strategic microbial species, whose activation, *e.g.*, by administering probiotics, can help reignite the entire microbiome – driving all other species back to their desired abundance.

To understand the roots of this seemingly *too good to be true* recovery scheme, we refer, once again, to our first example – the defibrillator. How can such an uncontrolled intervention achieve such a complex task as regaining consciousness? The answer is that the defibrillator is *not* what revives our knocked-out protagonist. It is the protagonist herself. Indeed, the functional state is ingrained in the human body – it is a built-in mode that our body knows, by design, how to sustain. Hence, all that we need is a strong enough jolt, to push our body out of the undesired phase. It is then the body's ingrained mechanisms that do the rest.

The math behind recoverability is strikingly similar. Complex biological, social and technological systems exhibit specific predetermined states. They can *find* these states on their own, based on their internal hardwired dynamics. Our single-node reigniting is, therefore, simply the jolt – the defibrillator - pushing them out of their failed state, and helping them innately reactivate their *a priori* hardwired functionality.