12 Conclusions and Perspectives

"As Pity and I have been attending some religious education before our marriage, I have found you an excellent quotation: 'And further, by these, my son, be admonished of making many books there is no end; and much study is a weariness of the flesh' (Ecclesiastes 12:14). Don't you think it is time to finish your book?" I have good news for you, Spite! We are indeed approaching the end. In this, the last chapter I will first summarize everything we have learnt about the weak-link-induced stabilization of complex systems. Then I will spend some time redefining weak links and stability. Finally, another set of advice will follow: how to build proper links in your own life. Keep this advice, Spite. Your child may need it even more than you do.

12.1 The Unity of the Weakly-Linked World: A Summary

Tables 12.1–12.3 summarize the most important effects of weak links discussed in all the preceding chapters. It is clear from the tables that we have more than a dozen examples in which the stabilizing effect of weak links has been established for a wide variety of networks. Additionally, in another dozen examples, weak-link-induced network stabilization seems to be quite plausible. Although a general proof for weak-link-induced network stability is still lacking, I hope you will agree that this wide array of demonstrations cannot be a matter of pure chance. Weak links do indeed stabilize a lot of complex systems.

Weak links came as a great surprise to me. It was not so much their existence, which is obvious, but their importance that was the new message from my reading and which constitutes the main message of this book. These links form most of the links inside and around us and stabilize most of the networks we have ever had or accompanied.

I owe a great deal to weak links. Besides stabilizing me during the process of writing this book, weak links have given me a good opportunity to demonstrate the strength of the network approach.

Table 12.1. General effects of weak links in networks

Weakly-linked elements	Stabilized network	Stabilized function	Chapter and key reference
Network modules and networks	Various types of network	Help to link modules and to build upper networks	Sect.2.4; Csermely, 2001a; Degenne and Forse, 1999; Granovetter, 1973; Maslow and Sneppen, 2002; Rives and Galitski, 2003; Spirin and Mirny, 2003
Society members	Social nets	Establishment of small-worldness; better network navigation; better innovation	Sects. 2.1 and 2.4; Dodds et al., 2003a; Granovetter, 1973; 1983; Skvoretz and Fararo, 1989
'Distant' network elements	Various types of network	Help relaxation by distributing perturbations	Sect. 3.2; Ghim et al., 2004
Network modules	Various types of network	Help netsistance (network integrity) by disjoining modules	Sect. 3.2; Sethna et al., 2001; Sornette, 2002
Network elements	Various types of network	Serves as a 'reserve' which can be broken during stress and rebuilt after	Sects. 3.4 and 6.3; Granovetter, 1983
Oscillators	Various types of network	Helps to achieve stable synchronicity	Sect. 3.5; Blasius et al., 1999; Bressloff and Coombes, 1998; Gao et al., 2001; Lindner et al., 1995; 1996; Strogatz, 2003

I hope I have convinced you that networks and their general rules provide an extremely useful conceptual framework to understand the world inside and around us.

The different levels of the nested networks behave as a multidimensional puzzle and offer us a great tool to identify their missing elements or discover the missing links between them. Recent advances in genetics give excellent examples of cross-network annotation of existing, but in its present form rather useless information (Bergmann et al., 2004; Stuart et al., 2003). This cross-fitting works best at the level of analogies, rather as this book often builds on analogies. I have to note here that I agree with Rose (1997), who warned of the danger of analogies as a source of wishful thinking.

☺☺ **The most important and most favored hypotheses of the book.** Let me list some of the analogies that highlighted novel ideas in the preceding chapters. Most of them are only guesses at the moment, so I have marked this box with two smiley faces. I apologize for the fact that one or two items are actually only three-smiley dreams. The small smiling faces in front of each statement indicate its potential importance according to my current subjective judgment.

Table 12.2. Demonstrated examples of weak-link-induced network stabilization

Weakly-linked elements	Stabilized network	Stabilized function	Chapter and key reference
Water and atoms of proteins	Proteins	Protein structure and conformational transitions	Sect. 5.3; Barron et al., 1997; Brinker et al., 2001; Csermely, 1999; Klibanov, 1995; Papoian et al., 2004
Proteins (e.g., chaperones)	Cellular protein net	Cellular phenotype	Sect. 6.2; Rutherford and Lindquist, 1998
Motor unit oscillators	Muscle	Movement precision	Sect. 7.3; Semmler and Nordstrom, 1998
Social actors	Psyche	Psychological well-being	Sects. 7.5 and 10.3; Degenne and Forse, 1999; Freud, 1915; Kawachi and Berkman, 2001; Kunovich and Hodson, 1999; Veiel, 1993
Animals	Animal community	Group survival, group cohesion	Sect. 8.1; Noe, 1994; Silk et al., 2003
Females after menopause	Social net	Infant survival, group cohesion	Sect. 8.2; Connor et al., 1999; Lusseau, 2003; Silk et al., 2003
Society members	Society	Social cohesion, innovativeness, efficiency	Chap. 1, Sects. 8.3 and 10.3; Degenne and Forse, 1999; Granovetter 1973; 1983; Putnam 1985; 2000
Firm employees	Firm social net	Firm efficiency, resistance, innovativeness	Sects. 8.4 and 10.3; Cross and Parker, 2004; Dodds et al., 2003b; Fukuyama, 1995
Firm owners and firm	Ownership network	Firm survival	Sect. 8.4; Stark and Vedres, 2002
Owners and firms	Portfolio	Profit	Sect. 8.4; Stark, 1996
Participants of (pseudo)-grooming, small-talk, gossip, etc.	Social net	Psychological well-being, social cohesion	Sect. 8.6; Dunbar; 1998; Szvetelszky, 2003
Scenes	Drama	Plot	Sect. 9.2; Stiller and Hudson, 2005
Items of town architecture (districts, houses, etc.)	Town	Traffic, town life	Sect. 9.3; Salingaros, 2004
Software elements	Software (especially after refactoring)	Program	Sect. 9.4; Brown et al., 1998; Fowler et al., 1999
Consumers and prey	Ecosystem	Ecosystem stability	Sect. 11.1; Berlow, 1999; Blasius et al., 1999; Garlaschelli et al., 2003; McCann et al., 1998; Neutel et al., 2002

Table 12.3. Conjectured examples of weak-link-induced network stabilization

Weakly-linked elements	Stabilized network	Stabilized function	Chapter and key reference
Atoms	Crystal	Cohesion	Sect. 5.2; Ball et al., 1996
Water and atoms of RNA	RNA	RNA structure and conformational transitions	Sect. 5.3; Csermely, 1997
Enzyme functions	Metabolic net	Cellular metabolism	Sect. 6.2
Transcriptional modulators, DNA	Gene expression network	Transcription	Sect. 6.2
Cytoskeletal proteins	Cytoskeleton	Cell rheology	Sect. 6.2
Hormonal effects	Hormone network	Hormone response	Sect. 6.4
Immune cells	Immune system	Immune response	Sect. 7.1; Brede and Behn, 2002
Blood vessels	Blood circulation	Blood supply	Sect. 7.2
Neurons, neurotransmitters, astrocytes	Neural net	Neural function, learning and consciousness	Sect. 7.4
Words	Language	Meaning	Sect. 9.1
Electronic circuit elements	Electronic circuit	Circuit function	Sect. 9.5
Market actors	Market	Market	Sect. 10.1
Elements of all ecosystems and the environment	Gaia	Our past, present and future on this Earth	Sect. 11.3

- ☺ ☺ ☺ The basic statement of the book: weak links stabilize all complex systems.
- ☺ Levy flights represent our evolutionarily conserved sense of scale-freeness, showing a disturbed relaxation: the scale-freeness of games, music, and all types of art are reflections of this evolutionary heritage (Sects. 2.2 and 9.2).
- Music helps learning due to a better synchronization of our neurons. This is achieved by the stochastic resonance of neuronal oscillations with the pink noise of music (Sects. 3.1 and 3.5).
- I suggested a large variety of potential self-organized criticality phenomena (adolescent psycho quake, coughing, crying, firm reorganization, gossip, laughter, lightning, sex, wooing, etc.; many sections starting from Sect. 3.2).
- ☺ I gave three novel examples of topological phase transitions of networks: cell death, animal communities and turning points in history (Sects. 3.4 and 10.2).
- ☺ The rather controversial, but intriguing idea was raised that synchronization can be achieved between networks at different levels. This

trans-network sync is especially induced if the sync is very strong at one of these network levels (Sects. 3.5 and 7.4).

- ☺ ☺ Weak links make the stability landscapes smoother, e.g., energy landscape, fitness landscape, innovation landscape, diegetic landscape, etc., and facilitate transitions of the respective networks between their local equilibrium points (many sections from Sect. 5.2).
- ☺ Chaperones and other proteins buffer cellular noise and diversity due to their weak links (Sect. 6.2).
- Organelle diversity in cells acts as a stabilizer of higher eukaryotes (Sect. 6.2).
- ☺ Planned and efficient disintegration of the cellular net occurs during apoptosis (Sect. 6.3).
- ☺ Pink-noise-regulated treatment protocols are helpful against cancer (Sect. 6.4).
- ☺ Low-affinity, multitarget drugs are more helpful in several cases than single-target, high-affinity drugs (Sect. 6.4).
- ☺ The aging process displays a preferential deterioration of weak links, which leads to increased noise and destabilization of aging networks (Sect. 6.4).
- Intermediate motor unit synchronization is a weak-link-induced form of movement stability. Birth is characterized by an extensive sync and high fluctuation rate between motor units of the uterus (Sect. 7.3).
- ☺ ☺ The psyche can be assessed as a network with strong and weak links. Weak links are stabilizing here as well (Sect. 7.5).
- ☺ ☺ The SMALL and BIG phenotypes correspond to the STRONGLINKER and WEAKLINKER personality traits, respectively (Sect. 7.5).
- ☺ Grandmothers have more time and opportunity to establish weak social links. Weak-link-induced stabilization of the animal and human social groups may be a novel explanation for the existence of the menopause (Sect. 8.2).
- ☺ ☺ ☺ Diversity-tolerance is extremely important for the stabilization of society (Sect. 8.3).
- ☺ Women play a central role in the stabilization of society. (This may contribute to the development of many critical areas of the world, like Afghanistan, the Middle East and the Balkans; Sect. 8.3).
- ☺ ☺ Due to the slow change of the SMALL phenotype to the BIG phenotype, which is able to build stabilizing weak links, we should wait 2 to 3 generations of well-being before attempting to build democracies in developing countries (Sect. 8.3).
- Fringe areas have a general importance in the organization of complex networks. Brain intermodular fringe regions, engineering pidgin formalizations, architectural transition areas, and software design patterns are all very important examples of this same phenomenon (Sects. 7.4, 8.4, 9.3, 9.4 and 9.5).

- Gossip and slander build weak and strong links in a social group, respectively. This may be what underlies their stabilizing and destabilizing roles (Sect. 8.6).
- The 21st century developed a wide variety of pseudo-grooming and link strength relativization (Sect. 8.6).
- Superman exemplifies weak-linking and gender relativization (Sect. 9.2).
- Similarly to crying, laughter, clapping and stadium waves, synchronized relaxation acts as a source of catharsis (Sect. 9.2).
- Great masters, great architects and market gurus are people with exceptional cognitive abilities who think at least to 6th order (Sects. 9.2, 9.3 and 10.2).
- ☺ Scale-freeness in architecture is a source of improved relaxation and psychic well-being (Sect. 9.3).
- ☺ ☺ Weak links are key contributors to social capital (Sect. 10.3).
- ☺ ☺ ☺ This is the place for the synthesis of the next section, the coda I promised before.

I must admit that most of these analogies are rather hypothetical. Some of them are unbelievable, some may stretch the analogy beyond an acceptable measure, and some may eventually be proven to be wrong. However, the list is rather impressive and demonstrates the benefits of the network approach, going beyond the reductionism that pervaded most areas of science in the second half of the 20th century.

Scientific reductionism helps to conceal the fact that we are unable to grasp the whole, and need to analyze the details. Gould and Levontin (1979) warned against the dangers of extreme reductionism in their famous essay on the spandrels of San Marco. Rose (1997) describes numerous elements of reductionism:

- reification, which converts a dynamic process into a static phenomenon,
- arbitrary agglomeration, treating different reified features as arbitrary exemplars of a common character,
- improper quantification, adding an arbitrary number to agglomerated reified features,
- confounding metaphor with analogy or homology.

In contrast to reductionism, networks help us to regain a holistic view of our life. There is every reason to hope that ‘networkism’ will never develop into a new ‘religion’. The network approach is an immensely beautiful general method, and not a monolithic belief. Moreover, it is not a holistic view without details. Networks offer you both the generality of rules *and* the delicate details. You may remember the nested networks. If you keep your distance, they behave like a point. If you go close to them, they will suddenly become a whole world.

12.2 Revisiting the Definitions: A Synthesis

In the last section I summarized our knowledge of the basic hypothesis of the book, i.e., that weak links stabilize all complex systems. I still owe you a definition of weak links and stabilization. In this section I will try to say more about both of them.

Warning! Danger zone! As you proceed through this section, you will find some rather far-fetched ideas on the possible use of strong and weak links as a new approach to describe the stability of complex systems. Perhaps I should have written the whole section in a smiley box. However, I think these ideas are rather novel and important enough to deserve a larger font than that here. I have thus kept to the regular typography for the text in what follows, and ask you to bear in mind that most of the statements are only hypothetical ... as yet!

Weak Links: The Definition Remains Unchanged

I must admit right at the outset that, even after so many chapters and examples, I have no better definition for weak links than the one I gave in Sect. 4.2. The examples of Tables 12.1–12.3 gave me the clear impression that the actual ratio of stabilizing weak links is highly dependent on the system properties and cannot therefore be generally defined. The 'weakness' of the weak links may also vary along these lines. Moreover, the exact position of weak links is also important. It is quite plausible that we may need different amounts of weak hubs (date hubs; Han et al., 2004; Luscombe et al., 2004), weak bridges or 'simple' weak nodes to stabilize a complex system. Much more experimental work, methodological precision and modeling effort is needed to see whether any generalization or classification can be made with regard to these numbers.

In the absence of adequate knowledge for a theoretical or numerical approach, I can only resort to the experimentalist definition of Sect. 4.2: A link is defined as weak when its addition or removal does not change the mean value of a target measure in a statistically discernible way (Berlow, 1999).

Stability of Complex Systems: A Reintroduction

Fortunately, much more can be said about the definition of the stability of complex systems after the numerous examples of the preceding chapters. Reiterating the remarks of Sect. 4.3, network stability can be defined either as parameter stability or as network persistence (netsistance). The criterion of netsistance is rather simple: the network has to keep its integrity, meaning that most of its elements should stay linked to each other. In other words, the so-called giant component of the network should be preserved. The studies I have read so far have not provided any clues as to how to connect weak links and netsistance. Perhaps further development of the topological phase transition theory of Tamas Vicsek and colleagues (Derenyi et al., 2004; Palla et al., 2004) will give more data to be able to discuss this field better. But in the absence of such data, I will restrict my thoughts to the parameter stability of networks.

The parameter stability of networks usually ‘overshadows’ netsistance. If a network can stabilize most of its parameters, it is rather unlikely that it will grossly change its topology and undergo a massive topological phase transition.[1] Assessing the role of weak links in the parameter stability of networks will give us some rather big surprises and novel thoughts by itself. Let me approach this enormously complex field by starting from the simple and moving towards the more difficult. First I will consider only the topology of weak links in complex networks, and I will propose a novel type of Le Chatelier principle showing how networks may counteract the effect of destabilizing perturbations. Next I will introduce the energy-type network parameters, and I will describe various stability landscapes, proposing a novel role for weak links in making the local minima of these stability landscapes more accessible. Finally, I will move one step closer to the real world and show what happens if a change in a network element provokes changes in other network elements. Under these conditions the stability landscape itself is also continuously changing. Several simplified subtypes of this incomprehensible complexity, such as the Nash equilibrium or supermodularity have become fundamental elements of game theory. I will end my discussion by showing that weak links help to simplify the multiple stability landscapes and also make the otherwise hopeless search for equilibrium easier under these complex conditions.

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[1] I should note here that the connections between these two types of stability have not yet been worked out either.

Le Chatelier Principle for Networks

If a perturbation hits an element of the network, it becomes unstable and will be unable to make strong links with any of its neighbors. Sometimes strong links will turn into weak ones, but in most cases a large number of links will break and only a few, mostly weak new links will form instead. In the next step, more and more perturbations hit the network. In consequence, the ratio between strong and weak links shifts towards the latter. As a result of the increasing amount of weak links, the network becomes more stable. Consequently, if the perturbations have not overwhelmed the network, the network automatically stabilizes itself by converting strong links into weak ones (Fig. 12.1). This may be regarded as a Le Chatelier-type principle for complex networks.

"Granovetter (1983) showed that, in the case of high unemployment or any other type of increased everyday stress, weak links are broken and people tend to rely on strong links. Don't you think that there is a contradiction between this statement and your Le Chatelier principle?" Well done, Spite! Many thanks for this remark. The contradiction here is only apparent. The Granovetter statement referred to static network behavior which can be observed as an average

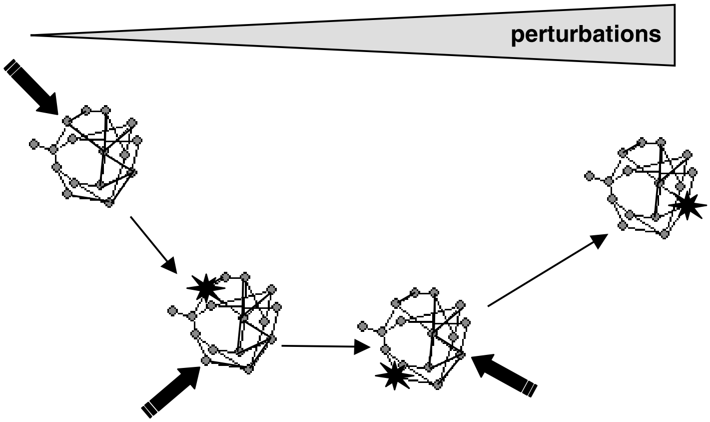

Fig. 12.1. The network Le Chatelier principle. Incoming perturbations (*thick arrows*) first destabilize the bottom networks of the perturbed network elements (*black stars*). The unstable element turns some of the strong links (*thick lines*) into weak ones (*thin lines*). As a result of the increasing amount of weak links, the network becomes more stable. Note that only two link strengths (strong and weak) are marked in the illustration. In reality, link strength has a continuous spectrum and the modification of links after a perturbation has a much more complex pattern than the one depicted here

in the long run. Indeed, it is true that in the absence of resources, the network does not have enough energy to build up weak links on top of the most essential strong ones. However, the network Le Chatelier principle refers to dynamic processes. Even these 'all-strong' networks turn some of their contacts into weak ones if perturbations arrive. In their case, this may be more transient than in other networks.

Stability Landscapes, Punctuated Equilibrium, and Netquakes

In spite of the initial statements above, network topology is clearly not enough to analyze the stability of networks. We may get a better picture by introducing the stability landscapes. The landscape approach usually picks two parameters of the network and plots the stability criterion (e.g., energy) as a function of these two parameters in the third dimension (see Sect. 6.2 and Fig. 12.2). Obviously, this three-dimensional approximation is an oversimplified version of real life, where hundreds of parameters may change, and we would need a hundred-and-one dimensions to describe them. The landscape approach was first introduced by Sewall Wright in 1932 and has been successfully applied to describe the stability of proteins (energy landscape; Bryngelson and Wolynes, 1987; Bryngelson et al., 1995; Dill, 1985; 1999), species evolution (fitness landscape; Kauffman and Levin, 1987) and the innovation process (innovation landscape; Kauffman and Levin, 1987; Tyre and Orlikowski, 1994).

The stability landscapes of complex systems are rugged. They have many local minima, separated by smaller or bigger saddles. Often the minima are hierarchical and show modularity (Ansari et al., 1985). The heights of the saddles (the extent of free activation energies) may often show a scale-free distribution (Yang et al., 2003).

Due to the rugged surface, the temporal dynamism describing the transfer of the network from one local minimum to another on the stability landscape does not show a continuous change. Shorter or longer segments of relative stasis are followed by a sudden shift to a novel stability landscape minimum which may often result in a drastic change of most network properties. This phenomenon is called punctuated equilibrium, following its powerful description for the majority of evolutionary processes (Gould and Eldredge, 1993). Punctuated equilibrium was proposed to characterize the development of many complex systems like protein folding (Ansari et al., 1985; Yang et al., 2003), economics (Schumpeter, 1947), innovation (Tyre and Orlikowski, 1994),

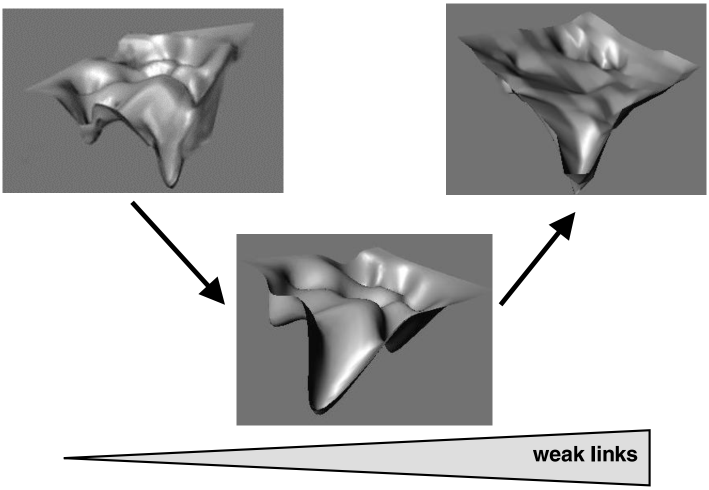

Fig. 12.2. The stability landscape of networks. Weak links smooth the stability landscape

institutions (Aoki, 1998), software design (Crutchfield, 1994), and scientific progress (Kuhn, 1962). In punctuated equilibrium, stasis, especially the stasis during intensive environmental changes, is not just a period when nothing happens, but an active phenomenon (Gould and Eldredge, 1993) where the network requires stabilization by weak links.

The dynamism of punctuated equilibrium resembles the various quakes we have met since Sect. 3.2. Netquakes are signature properties of self-organized critical systems. Indeed, self-organized critical networks have been shown to have punctuated equilibrium (Kauffman and Johnsen, 1991; Bak and Sneppen, 1993; Sneppen et al., 1995). *"This seems to be so general that we may say we are living in a life quake."* Thanks for the life quake, Spite. This is a beautiful expression. However, it may not be true. As I mentioned above, self-organized criticality is in a punctuated equilibrium. However, not all punctuated equilibrium is a result of self-organized criticality. If the interaction strength of network elements is very diverse, too weak or too strong, self-organized criticality may not develop (Sethna et al., 2001). However, the complex system might still manifest the features of a punctuated equilibrium under these conditions.

Weak Links Improve the Accessibility of Stability Landscapes

Following this introduction, I now come to the novel part of the discussion. How do weak links influence stability landscapes and punctuated equilibrium? Table 12.4, which extends Table 4.1 in Sect. 4.1, summarizes the features of network stability in the presence and absence of weak links. The characterization shows the clear differences between networks having many or only a few stabilizing weak links. The take-home message is as follows: in the presence of weak links, stability landscapes become smoother. In other words, weak links make the punctuated equilibrium less punctuated.

☺ **Too many weak links may destroy equilibrium.** The involvement of weak links in lowering the saddles of a stability landscape gives a novel meaning to the overconnected and therefore unstable networks mentioned in Sect. 3.3 (Fink, 1991; May, 1973; Siljak 1978; Watts, 2002). If the network has many weak links, the stability landscape becomes very smooth. This means that most saddles become low in the stability landscape and practically all energy minima become accessible. If there is a well-defined, absolute energy minimum, the network will instantly go there and remain there, so that equilibrium is easily achieved. However, if such an energy minimum does not exist, the network may shuffle between various energy minima which are close enough to each other to offer an equally good place to stay, and equilibrium is never achieved. In the latter, multi-minimum landscape, the presence of higher saddles and increased roughness may make most of the competing local minima inaccessible, and may help one of them to be found as a possible equilibrium.[2]

☺☺ **Weak links help the convergence of bottom network stabilities to top network stability.** When speaking about network stability, we should not forget about nestedness. All elements of the top network are themselves bottom networks. All of their links are in fact a part of a complex synchronization (or desynchronization) phenomenon. I have already mentioned cross-network stabilization from top to bottom networks and from bottom to top networks in Sect. 4.3, referring to the stabilizing mechanisms of the top networks exerted on bottom networks,[3] as well as to the stabilizing

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[2] I am grateful to Cleopatra Ormos for this idea.

[3] These were the mechanisms to (a) stabilize, (b) segregate, or (c) disassemble the unstable bottom networks.

Table 12.4. Network stability in the presence and absence of weak links. The content of Table 4.1 in Sect. 4.1 is repeated at the top of the present table, while novel statements are placed at the bottom of the table. The term 'energy' may refer here to fitness, design efficiency, market value, story integrity, etc., depending on the type of stability landscape (energy, fitness, innovation, economic, or diegetic landscapes, respectively)

Network has many weak links	Network has few weak links
Long-range contacts give small-worldness, modules are well-connected	Average distance between elements is large, modules are sparsely connected
Behavior of bottom networks is optimally synchronized, giving small fluctuations	Bottom networks are either tightly coupled with large fluctuations or behave independently of each other
Communication is good in the network, relaxation goes smoothly	Communication is restricted in the network, relaxation is disturbed, relaxation avalanches may occur
Noise is easily dissipated or absorbed in the network	Network is noisy and noise stays in segments of the network
Network is integrated and behaves as a whole	Network is segregated and behaves as an assembly of its constituent modules and bottom networks
Changes are dissipated and occasional errors are isolated, so that the network is stable	Changes and noise persist, the network is error-prone and unstable
The saddles of 'activation energies' are transiently lowered. The transition between local energy minima is smooth	The saddles between local energy minima are high. The transition between energy minima is difficult
Relaxation proceeds undisturbed	Relaxation is blocked
The parameter space of the stability landscape is 'discovered' by the network. Chances of finding the minimal energy state are high	Large segments of the parameter space of the stability landscape are inaccessible to the network. Chances of finding the minimal energy state are low
The network is not noisy. 'Unusual' transitions between energy minima do not occur. The most probable status of the network is generally predictable	Due to the blocked relaxation, the network is noisy. On rare occasions the network noise (especially pink noise) allows highly unusual jumps between energy minima. The most probable status of the network is difficult to predict
The network is plastic. After a jump to another energy minimum the reconfiguration of the network is easy. Novel weak links are established, which stabilize the network in the novel state, deepening the newly found energy minimum. Once the network has reached a new state, it may stay there, unless a neighboring saddle gets lowered again	The network is rigid. After a jump it does not change. Consequently, it will not 'adjust' to or 'fit' the novel state. Since the energy minimum of the novel state has not been deepened, the energy can only be lowered by another jump

efforts of the bottom networks on the environment,[4] respectively. However, there is also a remark here from the standpoint of weak links. If the top network is not integrated, the individual bottom networks will remain in their own optimum state, and will not be forced to observe the optimum state of

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[4] These were the stabilization efforts of the bottom networks on any environmental parameter or their symbiosis.

the top network. Integration of the top network is only achieved by the proper ratio of strong and weak links between the bottom networks. In other words, the cooperation of bottom networks needs weak links. This is related to the proper level of bottom network synchronization, which is also promoted by weak links, as I mentioned in Sect. 3.5.

Sorting and selection: a new difference. Vrba and Gould (1986) emphasized the difference between sorting and selection. They described selection as one of the causes of sorting. Using the effect of weak links described above, I may add that, in the presence of stabilizing weak links, the actual sorting will converge upon (obey) the underlying selection sooner than in their absence. Weak links facilitate the search for the optimum state on the fitness landscape (selection) and provide a better fit between the actual outcome (sorting) and the long-term goal (selection).[5] Obviously this does not change the difference between selection, which may operate at a certain level of nested networks, and sorting, which may be observed at the same level or any other levels above or below.

System Complexity Induces a Rugged Stability Landscape Which Makes Further Development Difficult

The complexity of the structure of the energy minima of the network may increase in parallel with the complexity of the network itself. Using the landscape representation, this means that complex systems have a more ‘rugged’ stability landscape. These stability landscapes may have more local energy minima and these minima may be separated from each other by larger saddles. Kauffman and Levin (1987) reached similar conclusions when they analyzed their fitness landscape model. They showed that, with increasing complexity, access to the best optimum becomes more difficult. Let me give a few examples to make this general statement clearer:

- Complex proteins have a more rugged energy landscape. A complex protein has more folding problems than a simple one, and the search for the energy minimum becomes more demanding as complexity develops (Bryngelson and Wolynes, 1987; Bryngelson et al., 1995; Csermely, 1999; Dill, 1985; 1999).
- Complex organisms may have a more rugged fitness landscape. A bacterium in our bowels may find a new phenotype much more easily than a squirrel.

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[5] If this assumption is true, the evolution of omnivores (with lots of weak links) should be generally smoother than the evolution of herbivores or carnivores.

- Complex designs may have a more rugged innovation landscape. A washing machine can be redesigned more quickly than a Boeing 777.
- Complex novels may have a more rugged diegetic landscape. *Little Red Riding Hood* can be more easily made into a video clip than *War and Peace*.

"This sounds tragic. According to this, the more complex we become, the more we get trapped by the 'frozen accidents' of our great-grandparents." Do not despair, Spite. First of all, without the frozen accidents of our great-grandparents we could not develop and maintain our complexity (Gell-Mann, 1995). Secondly, there is an almost automatic solution to escape from this catch-22 situation. I will give a possible answer below.

Four Mechanisms to Facilitate Changes in Complex Systems Despite Their Rugged Stability Landscape

Complex networks learn to extend their local stability islands (escape route 1). Self-organizing complex systems have the luxury of degenerate subsystems, which give a better error tolerance to the whole. Better error tolerance will extend the local stability island. A larger error tolerance allows higher designability.[6] As an example, more complex protein structures have a higher designability, i.e., there are more individual structures fitting the stability criteria of the same native structure (Li et al., 1996; Tiana et al., 2004). Increased designability is a consequence of the increase in the local stability island in the energy landscape of the protein,[7] and it allows the development of diversity in compliance with local circumstances.

Complex systems learn to jump around the stability landscape (escape route 2). Besides higher designability, the buffering (stabilizing) effects of weak links, also allow the development of hidden diversity (see Sect. 6.3). Weak links prevent the detection of this hidden diversity by the environmental selection process. Stress decreases

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[6] Designability is the maximal number of individual solutions accommodated by the given design pattern, i.e., the maximal number of individual solutions fulfilling the stability criteria of the network environment (see discussion in Sects. 3.6 and 9.5).

[7] The increased thermal stability of the most popular 'superfolds' occurring in the folding simulation of a 27-mer heteropolymer provides an excellent example (Zeldovich et al., 2005).

the total amount of weak links, leading to a decrease in buffering capacity and forcing most of the previously collected hidden diversity to appear. This is the point when selection begins to act on diversity, when it is suddenly exposed, erasing most of it in the long run.

Let me transcribe part of the take-home message of Sect. 6.3: by the stress-induced release of diversity, the system may bridge the distance between local minima on the rugged fitness landscape. So far we see no difference between simple and complex organisms. However, the frequency of local, observed stress may have changed during the development of complexity. If bacteria form no biofilm, their stress is unavoidable, since the protective microenvironment is missing. With symbiotic events and with the development of multicellular organisms, local stress at the level of individual cells becomes less common. For our own cells, stress is a tiny island in the middle of the ocean of a more or less undisturbed homeostasis. Consequently, cells of more complex systems have more opportunity to collect hidden diversity, since the ‘discharging’ stress comes more seldom. However, when it does come, it leads to the discharge of a much wider spectrum of previously hidden diversity. The conditions for the complexity-dependent extra ‘jump’ are now fulfilled. In spite of the fact that the next stable island of the fitness landscape is less accessible due to the complexity of the network, the same increase in complexity means that the network can make bigger jumps around the fitness landscape and a new optimum can thus be reached.

Modernity mandates a safety net around innovators. The development of modern designs requires much better conditions for innovators than before. Not only does complexity increase as we go from simple prebiotic bacteria to human cells, but a Boeing 777 is definitely more complex than a coffee grinder from the early twenties. We have every reason to assume that the innovation landscape of the Boeing 777 is much more rugged than that of the coffee grinder. It is rather plausible to expect that a major innovation on a rugged innovation landscape requires an extended stasis (in the form of undisturbed creative freedom), compared with an innovation on a smooth innovation landscape. CEOs and science policy makers should learn from this. Quite paradoxically, if they want a faster innovation process for designs with high complexity, they should allow a longer period of undisturbed creative freedom to the developers than before. The establishment should be alerted to the need for more long-term science grants to provide an undisturbed creative environment, and also to the need to separate think tanks in the high-tech industry if we hope to develop complex systems further. *"If I have understood correctly, undisturbed creative freedom is not enough here. From time to time, good management should also create an unexpected, high-stress situation to reveal the diversity of hidden ideas which have been accumulating during the long stasis of undisturbed freedom."* Great idea, Spite, I could not agree more. However, premature stress will uncover premature ideas, and they may not span the required distance to the next stability island on the innovation landscape. To sum up, Spite, establishing the right direction for the innovation process needs a great deal of wisdom.

☺ **Weak links help the stability of both the bottom and the top network.** Weak links in the bottom network thus generate increased diversity by various means (increased designability and hidden variation). Increased diversity generates more weak links in the top network. This provides another nice example of the cross-stabilizing effects of nested networks.

☺☺ **Complex systems may have learned to optimize their search for the absolute stability minimum (escape route 3).**[8] In random networks relaxation is global. In complex networks relaxation becomes restricted to the local environment. As mentioned in Sect. 2.2, decreased network relaxation may increase the diversity of jump lengths[9] on the stability landscape. In this process the jump-length distribution approaches a scale-free distribution. This means that the network usually makes a rather small shift on the stability landscape. However, the network will occasionally make larger jumps on the landscape, and on very rare occasions, a very large jump will follow. Thus, optimally, the walk followed by the network may become a Levy flight, which is probably the most efficient way to explore the stability landscape (Vishwanathan et al., 1999). Thus a network may have three basic scenarios for exploring the stability landscape:

- If the network has a lot of weak links, it is close to a random network, relaxation is undisturbed, the stability landscape is smooth, transitions have a high probability, and the network may 'allow'

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[8] This escape route is more hypothetical then the first two routes. To mark this difference I have inserted two smiley figures. However, I think the content is important, and I have therefore kept the usual font size.

[9] The jump length here is obviously not a physical length, but denotes the difference between the parameter sets of the two local minima on the stability landscape.

itself the luxury of choosing a search strategy closer to a random walk than the optimal Levy flight.[10]
- If the network has fewer links, these links will differentiate into strong and weak links, the relaxation becomes restricted, the stability landscape is rugged, transitions have a low probability, and the network has to develop a hidden variability and compensate itself for the reduced number of jumps. The network will thus select an optimized, scale-free search strategy, i.e., a Levy flight.
- if the network has only a minimal amount of weak links, it will remain in the vicinity of the original minimum on the stability landscape and become 'frozen'.

It should be noted here that we need much more modeling and experimental effort to determine whether:

- these assumptions are true,
- they are general to all types of stability landscapes (energy, fitness, innovation, diegetic, etc.),
- there is a continuous shift between the three extreme search strategies (random, optimized scale-free/Levy flight and 'frozen'),
- the Levy flight is the most efficient search on stability landscapes,
- there are other search strategies for the absolute minimum of the stability landscape which have not been mentioned here.

Complex networks have rather elaborate mechanisms to regulate the amount of weak links in them (escape route 4). This is something we discussed in Chap. 6. As we saw in escape routes 1–3, not only do weak links improve the chances of complex networks achieving an inherent diversity (designability, route 1), and not only do they give them the opportunity to make jumps on the landscape (hidden diversity, route 2), but they may also help them to find the optimal strategy for these jumps (Levy flights, route 3). In addition, complex networks are able to increase and decrease the amounts of weak links in them as circumstances may require (route 4).

Weak Links Increase the Evolvability of Complex Systems

The propensity to evolve is called evolvability (Kirschner and Gerhart, 1998). This gives me a chance to restate the above take-home message

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[10] Obviously, this is not a conscious choice. Due to the fast relaxation processes, the network cannot do anything else but to shift the search strategy from an optimal scale-free search towards a random search.

in another form: weak links help to set the degree of evolvability of the network. This is very much along the lines argued by Earl and Deem (2004), showing that evolvability is a selectable trait.

Weak links regulate the smoothness of the stability (energy, fitness, innovation, diegetic, etc.) landscape. The absence of weak links makes networks frozen, while many weak links make networks plastic. If we have an intermediate quantity of weak links, we end up with complex networks, where the above four escape routes promote the evolvability of the system.

Le Chatelier-type principle for the evolvability of complex systems. Let me restate the take-home message of the above discussion in a shorter form. As the system grows more complex, it has more chance of stabilizing itself and its environment. As a consequence, it acquires a higher evolvability, which helps to preserve its chances for development in spite of the stricter requirements to accomplish this task.

The evolution of evolvability and our future. Alternating periods of stasis and sudden change are needed for the evolution of evolvability. In other words (Earl and Deem, 2004): “Populations that are subject to more severe environmental changes can produce lower-energy individuals [with greater fitness] than populations that are not subject to environmental changes.” As a hypothetical consequence of the above, the extinction of dinosaurs might not only have happened because of the cataclysms after the asteroid impact in the Yucatán Peninsula (Alvarez et al., 1980). They may also have been preceded by a longer stress-free period beforehand. We humans started to enjoy a rather stress-free period some time ago. Although the ‘stress-free’ centuries behind us are nothing on the evolutionary scale, the long-term consequences speak for themselves. *“Now I am beginning to regain confidence in our future. For us personally, this might be a disaster, but for humankind as a whole it might supply just the tension needed to keep our evolvability fit.”* Spite, I love your global optimism. However, we do not know very much about Gaia yet, so we would do better to avoid any critical events. If you keep diversity today, you help Gaia to stabilize *and* you increase the general evolvability, including your own (Earl and Deem, 2004).

Link management in scientific discoveries. Alternating periods of stasis and evolvability can be observed in a slightly different context if we survey scientific progress. When we try to describe a new observation, we often use a sequential approach of alternating 'focused' and 'fuzzy' segments. When we force our brain to work in the focused mode, we use Occam's razor to cut everything from the network of thoughts which is not absolutely necessary for the exact description of the subject. The focused mode makes the description concrete and scientific, but it cannot usually insert a brand new element into the solution. In contrast, the fuzzy mode is usually a brainstorming process, when we start to play and add a wide variety of possible ideas to the existing core of the solution to the problem. The fuzzy mode destroys the clarity of the description, but often advances our understanding in unexplored fields. The focused mode increases the roughness of the innovation landscape, while the fuzzy mode decreases it, most probably by decreasing and increasing the amount of weak links in our thought network, respectively. The fuzzy mode may be helped by sleep. Interestingly, when birds were continuously kept in the focused mode during song learning, the final quality of their song was impaired (Derégnaucourt et al., 2005).

Stable Networks Can Participate at the Next Level of Self-Organization

In all the above discussions relating to stability landscapes, an energy-type function was used as the criterion for assessing how 'good' a network was. This function may be energy itself, or fitness, or design efficiency, or market value, or story integrity, etc. What is common to all these? Why do they have to be optimized?

I should note here that all these functions are our own fabrications to make the 'goodness' of our systems tractable and measurable. This raises the following question: what *happens* when a network is 'good' and it reaches the minimal energy of the respective stability landscape? Networks become stable. Is this something that actually *happens*? In fact it is not. It is just another parameter we use to talk about goodness. *"I do not understand the big hassle about the 'what happens' question. Can you not figure out for yourself what happens, Peter? Survival happens. That is what happens – or not, as the case may be. It's not that difficult!"* Wow, Spite, you got really emotional this time. But you are right, survival happens, at least in the long run. But for the moment, it is only a probability. By the time survival actually 'happens', the stability of the system will have changed a thousand times. Survival is an integrative measure of an average stability, and it is not what I am looking for.

The prompt, energy-dependent and visible action of stable networks is self-organization. If the bottom networks have found their energy minimum and are able to stay at least minimally stable, they can become a member of a top network. Designs are used, firms are traded, proteins build cells, cells build organisms, organisms build ecosystems, and so on. So how far can this chain be continued? In fact, the chain goes on until we reach Gaia. And what does Gaia build? Where is Gaia used or traded? What is the link, what is the reward here? What makes the discrimination between the 'stable' states of Gaia possible? What is the larger network in this case?

☺☺☺ **The links of Gaia.** Here comes the three-smiley part. We may opt for three answers. The first answer is spiritual. Gaia builds God. If Gaia is stable, God accepts her. If we make her unstable, as we are doing right now, we had better switch to the second answer before we end up with an unintended scientific 'proof' of the upcoming Doomsday. The second answer poses Gaia ready for marriage. From time to time Gaia gets very close to the point when she should develop further by getting integrated into a larger network. Hopes are raised, Gaia looks around excitedly – and then sinks back into her unhappy spinsterhood again and again. In the absence of external stabilization, an inner reorganization follows. Another version of self-organized criticality may bring into play the recurring criticality of a lack of self-organization at the higher level. Are we approaching such a point? Is the next round of global frustration and reorganization close? Is it not high time for us to shift our resources from wars to exploring other worlds, other civilizations, to find the missing link that might help Gaia to stabilize and avoid the next criticality? We know practically nothing. These questions are either grossly premature or completely misdirected. But let me ask again here. Are these questions really premature? Are they really misdirected?

"Peter, this is thrilling." I agree with you, Spite. If I could, I would have attached seven smileys to the above box, like the stars we have on Metaxas. I have an excuse though. The third answer. Gaia does not build anything. More than that. Gaia cannot build anything. From the network point of view, we are a closed system here, being lonely, linkless, helpless and measureless. Gaia is slowly cooking in the greenhouse effect, with a logo on her T-shirt which says: "Watch out, you guys! Self-organization ends here." Does this sound sad? Looking at the good side of it, we have to be responsible. We have no outside evaluation, no influential link to take and no synchrony to grab and enjoy. Either we set and keep our own measures, or we collapse. Sorry, I have no better news for today.

When the Stability Landscape Changes: Network Games

We have moved very far away from weak links and network stability criteria. I am sorry about that. Networks are so general and so logical that they make you think the unthinkable. Nevertheless, it is high time to return to science again. In the last part we had quite a nice characterization of stability landscapes with or without weak links. However, the *whole* of the last part was wrong. Spite, do not look at me like that. I was not lying. I made an approximation. Most of the science we know is only an approximation. Approximations are our bread and butter here, since they make problems tractable.

Now the trouble with stability landscapes is that they change. Here comes nestedness again. When bottom networks develop, they are not in a sterile space. They interact with other bottom networks forming elements of the top network. As they interact, the responses of all the other bottom networks change the environment, and consequently change the stability landscape (Nowak and Sigmund, 2004; Ruthen, 1993). Imagine a hundred, no, a thousand bottom networks. As they start to interact and the stability landscape starts to change in ten thousand dimensions. What's the matter, Spite? Are you OK?

"Peter, if you continue, I am leaving. This is too much. It has become incomprehensible and unimaginable. How can our world be so complex?" I agree with you, Spite. The complexity of multiple stability landscapes (I will call them multi-landscapes in the rest of the book) is really beyond our cognitive abilities. I have some good news though. We are not the only dumb guys around: this is beyond everyone's cognitive abilities on Earth. Spite, do you remember Dunbar (2005) and his 6th order thinking? According to his assumptions, to understand the changes in a stability landscape with six interacting elements would require Shakespeare's cognitive level. I have very bad news here. A network with six elements is not a network. It is a mere network embryo. For typical networks, we would need to think to the 1 000th order, or maybe to the 10 000th. *This* is clearly impossible. We have to make things simpler. Some of the most brilliant human minds have been involved in this simplification for some time now. The result is called game theory. Obviously I have neither the knowledge nor the courage to make an overview of all aspects of game theory from the standpoint of networks and weak links here. Let me restrict myself to two examples which exemplify the logic of some of the available solutions to this exciting problem.

My first example is the Nash equilibrium. The concept of the Nash equilibrium was described in an extremely elegant, 28 line publication by John Nash (1950). If a game is in a Nash equilibrium, no players will gain any benefit from a change in the playing strategy, if all the other players keep their original strategy. In other words, in a Nash equilibrium there is a balance between the gains and costs related to aggressive behavior. From the point of view of multi-landscapes, the Nash equilibrium is a very special case in which every element of the network sits in a local minimum, so that there is no need to imagine the multiplicity of the stability landscape. If the game is able to reach a Nash equilibrium, the multi-landscape has been simplified to the (mono-) stability landscape we had in the last section.

The second example is supermodular games. These are non-cooperative games. In these games the actions of various players are completely independent of, but complementary to one another. This is assured by a set of criteria. The most important of them is that the game has multiple positive feedback: an increased activity by some players raises the benefits of a similar activity by others. Under these conditions an avalanche-like behavior will develop. Such a situation might be the adoption of a new standard in an area of technology or the collective withdrawal of money from an ailing bank. Under these conditions these games have and can reach a Nash equilibrium (Milgrom and Roberts, 1990; Topkis, 1979). If we imagine this concept on the multi-landscape, we may say that most of the multiplicity of the possible stability landscapes has been erased by the complementarity condition, and the remaining multi-surfaces may converge to a situation where the above condition that everyone sits in a local minimum is set. As the above examples show, the equilibrium may be a rather short-term equilibrium here since, once the standard is adopted or the bank goes bankrupt, the game comes to an end.

Generalizing the logic of supermodular games, we see that game theory often uses a principle of rational human behavior for a drastic reduction of the multi-landscape to a few dimensions, where the search for an equilibrium point (determined again by expecting rational behavior on behalf of all the actors) can be accomplished. A beautiful example of this approach is the book by Harsanyi and Selten (1988), which contains the core of their work establishing several basic concepts of game theory and resulted in their winning the Nobel Prize with John Nash in 1994.

Our efforts to reduce the multi-landscape towards a mono-landscape in human relationships are not just based on ad hoc decisions. We have a rather large set of jointly internalized behavior codes and strategies. The process in which we acquire these codes and strategies is called socialization. It happens in families, schools and all human groups we join throughout our lives. *"Wow! Are you saying that, when our despised geography teacher tried to discipline us, he was actually providing help to achieve a better and faster outcome in our future games?"* Yes, Spite, you have hit upon the point. Obviously, in many cases you may leave your original group and go to another, if you feel you cannot converge to the common mono-landscape model of the original group. However, if you decide to stay (or you cannot leave), you should converge to the mono-landscape, otherwise the group will not be efficient. I must note here that the geography teacher should have done the same. But it is not only geography teachers that have been invented in our culture to accomplish this task. Institutions, rules, norms, laws and roles were all developed to simplify the multi-landscape and to make the responses of our partners predictable in a given situation. All these elements of human culture reduce the dimensionality of multi-landscapes, and make the situations of our everyday life cognitionally tractable.

However, we still have to simplify the remaining multi-landscape after the application of pre-set rules. Segments of the multi-landscape may also be continuously excluded as mutually optimal strategies develop between players during a game. This then becomes an iterative learning process (Axelrod, 1997). As an example, in supermodular games, complementarity may develop as players increasingly restrict themselves to a subset of strategies which prove beneficial, and abandon those strategies which have performed consistently badly (Milgrom and Roberts, 1990).

As a last remark I do not want to give the impression that games or reduced multi-landscapes will always lead to a Nash equilibrium. In several cases, the network may just remain unstable, showing oscillations or completely irregular dynamics. Moreover, the complexity of multi-landscapes may hide a number of surprising equilibrium conditions.

Obviously the above lines were not an attempt to summarize game theory in a one-page manner. This extremely complex and exciting topic deserves a whole book by itself. I only wanted illustrate the type of logic game theory uses to solve the cognitive problem of finding equilibrium conditions from amongst the ever-changing multitude of dimensions and stability landscapes.

Weak Links Facilitate the Convergence of Multiple Stability Landscapes

To assess the role of weak links in the complex equilibrium between interacting network members, I will first make an artificial approximation in which I dissect the interwoven texture of weak and strong links of a network into a weak subnetwork and a strong one. Let me give a brief analysis of the role of game theory in the treatment of these two subnetworks:

- **Weak subnetwork.** Elements of the weak subnetwork do not interact appreciably. If one of the weak elements changes, the other network elements will neither be affected, nor change their playing strategy, whence the overall stability landscape of the network will not change. The stability conditions of the weak subnetwork are mostly predictable. Since elements do not interact appreciably, the use of game theory is not needed to find the stability conditions of the weak subnetwork.
- **Strong subnetwork.** Any change in an element of the strong subnetwork affects all its neighbors. As summarized in the previous part, even the mono-landscape of the strong subnetwork is largely unpredictable. Since any change in a given element may lead to a change in the game strategy of all its neighbors, the stability conditions of strong subnetworks are governed by the laws of game theory.[11]

The game theory of proteins and cells. So far I have not mentioned consciousness as a condition of game theory. The rules of the game are not only the rules which the players of the game accept, set or discover as conscious actors. Rules in this broader sense are all the simplifying conditions that can be applied to two or more networks when they engage upon a strong interaction with one another. Thus the application of the basic simplifying approach of game theory will help us to define the changes in the energy landscapes as proteins start to interact with each other (Kovacs et al., 2005), but also the stability landscape of individual cells, such as those of the immune or neural systems, as they form larger networks, and so on. Consciousness of the network elements 'only' gives the additional level of complexity that the network elements do not necessarily have to make physical contact in order to learn about each other's presence and incentives. From the assembly of the hundred thousand types of protein molecules which we usually call a cell, the only ones that will cause a significant change in each other's energy landscapes are those which make a protein complex and get into physical interaction. If these proteins were members of a conscious

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[11] Importantly, if the elements of the strong subnetwork are not complex enough to show any appreciable change after a change in their strong neighbor, there is no need to use game theory even for the equilibrium conditions of the strong subnetwork.

society, the cries for help from their fellows adjacent to the breaking mitochondrial membrane would certainly alarm most of them before the actual damage arrived in the form of oxidation or proteolytic attack.

After restricting the applicability of game theory to elements of the strong subnetwork, I will now add the two subnetworks together again and, keeping the strong and weak identification of the elements, assess the effect of weak links on the games of the strong subnetwork members. As we have seen before, weak links lower the saddles of the stability landscape and may even eliminate several local energy minima. They thereby reduce the ‘roughness’ of the mono-landscape. What might correspond to this situation in real games? Elements of the hypothetical weak subnetwork should not participate in the games themselves. However, they help the players to find the optimal solution faster. What do we call them? In real human games, they are usually called mediators, moderators, negotiators, arbitrators or appraisers. In fact, all the people mentioned in Sect. 8.3: friends, gossips, hairdressers, madams, priests and psychologists (the list can be continued!) are elements of the weak subnetwork helping the various games of our life.

As discussed in Sect. 8.3, all these weak-linking actors help to stabilize society. Now we have an additional element to explain how they do it. They simplify the multi-landscape by helping a faster and more efficient exclusion of the stability landscape segments containing nonprofitable plans for potential actions. Due to the weak links, this action is not unilateral, but is in most cases extended to all participating players of the game, which is not necessarily helped by the same weaklinkers. Thus weaklinkers allow a faster convergence of the ‘real players’ of the strong subnetwork towards equilibrium.

Do all weak linkers help this action? They most probably do. At least, they may provide an opportunity to simplify the multi-landscape *without* adding their own extra dimensions to it. In other words, weaklinkers do not increase multi-landscape complexity, since they do not have strong links and hence do not participate in the game.[12]

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[12] In the real world, my initial approximation does not hold: weaklinkers do participate in games themselves. In other words, all mediators participate in the game, since a fully impartial mediator may not even be efficient (Kydd, 2003). If weaklinkers have a few strong links, they will obviously also increase and not only decrease multi-landscape complexity. Since there are far more weaklinkers than strong – this is not only due to the scale-free distribution of link strengths described in Sect. 2.4, but also due to human cognitive limits, which in most games

Two examples. Although I promised not to give extensive examples from various games, I would like to mention the fact that in the minority game and in the binary evolutionary game, the game manifested a much smaller fluctuation if the players were non-identical (Challet and Zhang, 1997; 1998). Non-identical players may develop weak links and enhance the convergence of multi-landscapes.

Weak Links May Explain the High Assortativity and Clustering of Social Networks

Are all weaklinkers equally efficient at inducing the convergence of multi-landscapes? Most probably they are not. Fast convergence of two or more multi-landscapes towards each other is best achieved if weaklinkers persuade the two or more players of the game to adopt the same type of strategy. This works best if the weaklinkers really 'link' the two players with a strategy preference that provides a bridge between the players' strategy preferences. Thus the most efficient weaklinkers should be rather similar to both potential players to ensure a fast and efficient simplification of the multi-landscape. How will this requirement be reflected in the network structure? Similar elements should group together, because otherwise their decisions will never converge, and they cannot help each other to achieve this. This grouping is called assortativity and clustering.

As already mentioned in Sect. 8.3, social networks have these two rather specific features (Newman, 2003b; Newman and Park, 2003). The reason for this specificity remains largely unexplained. Games between similar strong subnetwork members, as well as efficient moderation received from similar weak subnetwork members, may significantly accelerate multi-landscape convergence. Members of technological or biological networks[13] experience a much smaller range of change in their stability landscapes as a result of the action of another network member. Consequently, they are not such a great help for multi-landscape convergence. Multi-landscapes may grow to a level of complexity requiring the help of assortativity for landscape convergence only beyond the level of social nets, ecosystems, 'evolutionary nets', and perhaps the networks of cells. Amongst these, only social networks have been sufficiently studied to be able to characterize their

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seriously restrict the number of strongly linked players – it is quite plausible that the net outcome of weak link contribution is a simplification of the multi-landscape.

[13] These networks all have a negative assortativity.

assortativity. Efficient simplification of stability landscapes may provide an additional and important explanation as to why assortative and clustered social nets were selected and kept by evolution.

Link relativization and game theory. *"I have an objection again. Clusters of social networks imply strong links. If I have two friends and they become friends with each other, then all three of us make strong links. Your theory that weak links simplify the multi-landscape cannot be applied here!"* Well done, Spite! This is a nice objection. However, you must bear in mind that you keep your strong links until the three of you are in good agreement. In this case the identical strategies themselves simplify the multi-landscape and you do not need any weak links to help the process. However, if a disagreement starts between two of the three, the third friend may want to help to rebuild the friendship between the two who disagree. This is now a typical weak-link situation, where the differing stability landscapes of the disagreeing friends are helped to converge by the mediation of their common friend. You may observe that the links were temporarily weakened between the mediator, who is not part of the disagreement, i.e., the game, and the other two friends.[14]

Open Questions and Summary

Many exciting questions remain open, such as:

- How do the above weaklinkers simplify fitness multi-landscapes?
- How do ecosystems tackle this problem?
- Can we make anything out of this at the level of our lovely old spinster, Gaia?
- Do protein complexes or cellular nets give us a new understanding of multi-landscapes?
- To what extent is this set of ideas valid for the diegetic landscapes of our best dramas, novels and films?

"And??? I am so excited! You cannot just leave these questions like this!" Sadly, I will have to leave them for now, Spite. We must leave something for the next book, you know.

Let me restate the take-home message here. In the first step, weak links make the definition of the equilibrium conditions possible with the development of mono-landscapes. In the second step, weak links make the search for the now-defined equilibrium possible by smoothing the mono-landscape. Without the multidimensional convergence

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[14] I am grateful to Zoltán Borsodi for this idea.

provided by weak links, the network would never reach equilibrium in most cases.

Link strength, probability and thermodynamics. Probability and thermodynamics in their classical interpretations assume the absence of strong and conditional interactions between the participants of the observed network. Thus, using the above distinction between weak and strong subnetworks, both concepts describe only the behavior of the weak network. We have to be extremely careful if interpretations, consequences or direct use of classical probability and thermodynamics ‘sneak in’ to our thoughts when we speak about the properties and behavior of strong subnetworks, where the ‘conditioned’ interactions of network elements often make ‘simple’ thermodynamical or probabilistic predictions useless.

Spite, please help me to check how comprehensible this important section has been. May I ask you for a summary? *“You trust me too much, Peter. This has been a rather difficult section. However, I will give it a try.”* Spite, I have to make something clear. It is not your fault if you do not understand this section or any of the others. It is my fault. My ideas were either badly formulated or simply not ripe enough to talk about them, if a person like you, after qualifying at a good high school, does not understand what is written here. Science is not science, or at least, not important science, if the essence of it cannot be formulated in common language for the layperson. *“It is nice of you to say that. I feel more comfortable about beginning my summary. First you described an interesting negative feedback effect in networks, hypothesizing that a perturbation may cause a shift from strong to weak links, thereby increasing the chances of the network getting stabilized. You also gave a detailed summary showing that weak links can smooth stability landscapes (you called them mono-landscapes) and make punctuated equilibrium less punctuated. As the last element of these equilibrium ideas, you extended the ‘guiding effect’ of weak links towards equilibrium to the multiple stability landscapes (multi-landscapes) of game theories. I was discussing this with Pity and we decided to talk more about our problems to each other and to our friends. It is rather silly not to use the available weak links to find the equilibrium of mutual respect and love in our everyday games. I liked your idea about the evolution of evolvability as complex systems develop and the links of Gaia were thrilling – as I noted there already.”* Spite, your summary was better than I could have made it myself. Many thanks!

Completing this section, I feel like a curious and stubborn child. Walking around in the attic I found a colorful and intriguing thread: weak links. I felt that there must be something exciting and unknown at the other end of the thread, and I started to pull it. I pulled, and I pulled. And all of a sudden the whole roof was falling down upon me. “Mathematicians tend to favor restricted definitions, engineers broad definitions, while physicists are somewhere in between” (Turcotte, 1999). What type of definition might fit a networker, or more precisely, a weaklinker, like myself? Natural networks are in continuous growth and remain forever unfinished. I do ask your forgiveness if you feel that the definitions of their links or stability also remain unfinished. Notwithstanding, I hope at least the attempts at definition were interesting and useful.

12.3 Prospects and Extensions

Having analysed the central statement that weak links stabilize all complex systems and discussed related definitions, I begin now by listing a few ideas on further studies in the context of weak links. In the second part of the section, I will outline the possible extensions of weak-link-induced stability to smaller and larger networks than those visited in the tours of Netland in Chaps. 5–11.

Spite, it is time for you to listen, as a future scientist. To begin with, I have already listed 29 novel ideas in Sect. 12.1. All of them may be starting points for exciting further research. Let me list here a few more ideas for further studies, which were put forward in the last section:

- Many examples of the stabilizing effects of weak links are only assumptions at present. The general, mathematical proof for weak-link-induced network stabilization is still lacking.
- Although there are numerous examples of the scale-free distribution of link strength in various networks, we do not know what the limitations of this distribution may be, nor how often we may find them, nor how general and how necessary they are.
- We do not know how the link strength and degree distributions are linked, i.e., we do not know the ratio of hubs having mostly strong or weak links. As an initial characterization of this problem, the ‘date hubs’ of the yeast networks (Han et al., 2004; Luscombe et al., 2004) are in fact weak hubs, since they establish only transient links with their partners. However, we do not know whether the contribution of weak hubs, weak bridges or the presumably overwhelming majority of simple weak nodes are more important in the stabilization of networks.

- We do not know whether weak links only stabilize networks with scale-free degree distribution, or whether they also stabilize random graphs, star graphs or fully-connected subgraphs.
- The network Le Chatelier principle requires a lot more clarification. Examples have to be given and a formal proof made, and the restrictions of its validity have to be explored.
- The evolution of evolvability will require many experimental, modeling and theoretical studies. Its connections with increasing system complexity seem to be especially important.
- Game theory will certainly go through a renaissance as it conquers more and more networks beyond social nets; even in its classical field of application, i.e., real, human games, the involvement of weak links and their possible connections with the assortativity and clustering of social networks deserve a great deal of attention in the future.

"These are nice ideas, but mostly for mathematicians or physicists. I am neither of these. However, spending such a long time with you and with this book, I have become really interested in weak links. What can I do now?" Spite, first let me thank you for putting aside your reservations and growing to like weak links in the end. In answer to your question, if I had not known you, I would have said: write an email to the address in the Preface of this book with your idea or area of interest. Since we have already been working together for quite a while, I am sure you will find a nice project from those started by the LINK group, after your marriage and the canoe trip, of course!

Do you remember Spite? When we made our trips into Netland, we started with molecules and finished with Gaia. These networks are so nicely nested inside one another that it is tempting to speculate whether there might be anything beyond? Most probably not. The network theory seems to be a really powerful approach to link vastly different systems, and show the general elements of their organization, dynamism and stability. However, like everything we have figured out here on Earth, networks are probably also anthropocentric and may well prove to be useless if we get too far away from human dimensions. In any case, I will make an attempt to extend the network approach both towards the bottom and towards the top – imploring your patience once again.

Particle net: where things might reverse.

In all the network changes covered so far in this book, the energy changes were modest. Their transformation to matter was negligible. What happens if the energy is so high that we cannot neglect this phenomenon any more? If we speak about elementary particles, can matter serve as a governing force behind transitions in the energy net in the same way as energy served as a governing force behind the transitions in particle nets? If a network is formed from particles, weak links between them correspond to a small probability of interaction between them, i.e., the particle to energy transition is small. If the network is formed from energy levels, weak links between them mean a small probability of transition between these energy levels, i.e., the energy to particle transition is small. In summary, weak links are those which least disturb the dual energy/particle behavior of the given system. Could this also contribute to the stability of the system?

Going to the other extreme, the Solar System and beyond, we find a scale-free density distribution in the hierarchy of stars, galaxies, intergalactic gas clouds, galaxy clusters and probably galaxy superclusters. The fractal property of the Universe was first predicted by Mandelbrot in 1977. By now it is a widely accepted fact.[15] However, it is still an open question as to where we will find the threshold between this scale-free distribution and the presumably isotropic and homogeneous Universe on the 'large scale', which is called the cosmological principle. The fractal property below 100 megaparsec can be explained by the action of gravity invoking a preferential attachment, or self-organization again (Baryshev and Teerikorpi, 2004; Gaite, 2005; Mahdavi and Geller, 2004; Pietronero, 1987; Sarkar, 2005; Wu et al., 1999).

What are the weak links in the Universe? Are the weak links in the Universe represented by the dark matter or the dark energy? Do we have something in the Universe which is currently unimaginable but provides stabilizing weak links? Do weak links really stabilize our Universe? Or is the whole network logic no longer valid here, so that the Universe does not have any weak links at all?

Laughlin and Pines wrote in their essay entitled *The Theory of Everything* (Laughlin and Pines, 2000): 'It is impossible to miss the similarity

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[15] Let me note here that the network structure of the Universe suggested by its scale-free density distribution should not be confused with a potential top network of the Gaia ecosystem. I have not found the faintest hint of the existence of this latter network.

between the large-scale structure recently discovered in the density of galaxies and the structure of Styrofoam, popcorn or puffed cereals." They also note that: "The central task of theoretical physics in our time is no longer to write down the ultimate equations, but rather to catalogue and understand emergent behavior in its many guises, including potentially life itself." I hope the present book has been able to show that networks are excellent vehicles for this cataloging task. Jiddu Krishnamurti (1992) made a clear distinction between knowledge and wisdom. In his teachings, knowledge is information about the world, whereas wisdom is our knowledge about the processes. I believe networks teach us wisdom in Krishnamurti's sense:

> Mental paradigms are models that simplify complexity, ideas that help to make sense out of the infinitely complex continuum which is reality. No idea can represent reality as it is. A paradigm merely represents a fragment of reality in a way that allows the mind to deal with it: it encodes a part of the world to the mind's specifications. A paradigm is formed and retained because it is useful, not because it is real. A scientific paradigm marks out a conceptual territory for exploration by observation and experimentation. It establishes a world view that defines which questions are worth studying and what answers might be expected. (Cohen, 1992a)

The extent of the usefulness of the network approach in general and the multiple stabilizing roles of weak links in particular remains an open question:

> When a scholar publishes a paper, it is a letter sent to unknown recipients. If the job has been well done, then with luck it may be found and read, perhaps years later .... (Myerson, 2001)

However, at least for me, networks and weak links already "establish a world view that defines which questions are worth studying and what answers might be expected". I owe a great deal to all those I have quoted along the way and also to those I have not quoted due to some regrettable oversight.

12.4 Weak Links and Our Lives

Networks and links not only organize our thoughts and stabilize both ourselves and our environment, but they also help us to develop. Our personal life behaves as a self-organizing network. Our capacity for trust is a signal of our inner stability, showing that we are able to further extend our own life net and universe net. As a result, we feel happy and enriched as our inner or outer networks extend.[16] If the development of our nets is continuously arrested, we start to die. This concluding section will give some advice on how to accomplish this lifetime commitment for our self- and universe-organizing task.

Life net. Life itself, with all its decision points and multi-landscapes, and all the possible but mostly *not* followed pathways, can be imagined as a network. We have very few major decision points, and a large number of small ones. At the big decision points, we might go in a thousand directions, while at the small decision points, we may only select from a very few options. Unfortunately, in this case a control experiment is not possible. We cannot start our life again to explore the choices we have not made. I am afraid the question as to whether the life net is scale-free will never be answered.

In Sects. 8.4 and 10.3, I listed several benefits of links. Links lead you to success. Top performers are distinguished by their well-developed social network. More importantly, links preserve your health (Cross and Parker, 2004). An appropriate social net helps you to control blood pressure, decrease your chances of dying from a heart attack, and improve your immune response (Putnam, 2000). So how should we develop and maintain our links? In fact, this is an inappropriate question. Link development on its own is not enough. A link always has and needs another end besides yourself. Moreover, stability can only be reached and preserved together. So an equally important question arises: how should we help others to develop and maintain their links? Here are some ideas:

- **Leave your gadgets.** If you feel isolated and alone, you may think you do not have links. This assumption is wrong. No one is linkless. Lonely people have their own set of links, but these links are misdirected. It is time to make your link inventory. You may actually play with that as you analyze your coming week. How will you spend your time? What is around you, where is your attention focused, and what is the target of your acts? What are the nodes to which your links lead you? Do you care about your car repair, new mobile, and the pool in the garden, or do you prefer to play with your children, or discover yourself and the wisdom within? If

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[16] I am grateful to Csaba Sőti for this idea.

your link inventory is gadget-oriented, it is high time you changed. If you are linked to gadgets, your main direction is downwards and not upwards. Your gadgets will not help your self-organization.

- **Get stabilized.** Unstable subnetworks cannot be part of a top network. Do not expect links if the only help you can offer is to destabilize your neighbors. You will be segregated as part of the self-healing process of the top network. Your life will be changed if you are able to get yourself just a little more stable. Why is this moment so important? Self-stabilization is a highly rewarding project. The smallest step towards your own stabilization will open new links to you, and these will help all the further steps ahead of you.
- **Develop trust.** Once you have improved your stability, you are ready to enjoy the benefits of the immense social net around you. But not only that. You will also enjoy all the other nets above and below. Obviously these indirect effects will be weaker and weaker as the distance between the nested networks grows. But your links are not only your gates into society. They also open the whole Universe to you. Cross-network stabilization may help to improve your health and make life smoother around you. How should you start to make links? Develop trust. How should you start to develop trust? Improve your stability.
- **Select and use your links.** The more links we have, the better our life will become. In fact, this statement is incorrect. If your links lead you everywhere, then you have no links. Moreover, you will have no time to maintain your links. If your links lead you everywhere, your links will become useless. Remember the instability of the over-connected system. The random network is a primitive net with low complexity. You deserve more than that. You need a careful balance of a few strong and a lot of weak links. Treasure all your links appropriately. Make special efforts to be a bridging person between groups with different habits and cultures. Give quality time to your links and use them. You should feel the joy of being linked. This is how you can initiate novelty, achieve success and stability, and be a part of the joyful synchrony these links allow us to develop.
- **Help others to get their links.** Cross and Parker (2004) call the really good link-makers energizing people. What is needed for this? (a) A vision that people can follow your ideas and not you yourself; (b) integrity that validates your vision; (c) a chance for contribution that leaves the path flexible to reach the common goal; (d) positive thinking that binds rather than separates. Relating these to the

terms listed above, (a) and (b) both correspond to your stability, (c) is your trust, and (d) is the joy of using your links.

You may have noticed that a few of the link-related pieces of advice are actually duplicates of those in Sect. 11.3. The stylistic error was intentional. Person- and wisdom-oriented links, a proper inventory of various link strengths and bridging links with the related trust, tolerance and diversity are the most important personal messages of this book. Let me ask you for the last time to take a deep breath, to drink a glass of crystal clear water, to relax, and most importantly: to think. Link management is not only a key for your personal well-being and success. It is the evolutionary duty of us all.

We have come close to the end of the book and it is time to say good-bye to you Spite. Let me thank you for all your criticism, help and companionship. *"That is very nice of you, Peter. I promise to try out the Levy flights on my honeymoon canoe tour with Pity. From now on, whenever we listen to music, we will also think about pink noise, and I have taken good note of all your advice to us and our child."*

This book was actually a link itself. A link to all the wide variety of networks we have visited together and a link for me to say something about the world – as seen from this head. I hope the book is an interesting mixture of 'true science', one- or two-smiley hypotheses, and more conjectural three-smiley beliefs. I have an excuse for the latter two, which are actually related to weak links:

☺☺☺ **Science and the weak cognitive links.** Science wants to give clear answers and thus provides strong cognitive links. When modern science started with Copernicus, Galileo, Newton and Descartes, it increased our inner stability, since it provided a few strong cognitive links which made the plethora of previous links weak, thereby stabilizing the system. However, one has to warn about the other extreme. Extremist positivism may give too much space to science. If thoughts such as 'what is not scientific is not valid and is not part of our world explanation' begin to emerge, we start to reduce our cognitive links towards the outside world to strong ones. Too many strong links destabilize us. Science should be modest, restrict herself, and always leave some ground free for the weaker cognitive links of religion, art and simple beliefs.

This book was about weak links. Here I want to repeat once more that weak links alone do not mean anything. Stable systems most probably need a scale-free distribution in link strength. Stable systems may try to approach a scale-free distribution in all dimensions. A perfect scale-free distribution in all imaginable dimensions and measures looks the same from all possible points on all possible scales. Scale-free then becomes free from any scales. The concept to name this uncompromising scale-freeness was figured out a rather long time ago: it is called God.[17] We are part of a 'background network' providing a net of weak links which are everywhere, and are based on affection, goodwill and love.

The final message: we should not worry, once we learn to accept affection, goodwill and love, we will remain stable. The weak links will stay with us until

THE END ...

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[17] I am grateful to Bálint Pató for this idea.

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