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explorations in education

Education and the New Science of Networks

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Linked: The New Science of Networks
by Albert-László Barabási
Cambridge: Perseus Publishing, 2002, vi, 280 pp.

Nexus: Small Worlds and the Groundbreaking Science of Networks
by Mark Buchanan
New York: W. W. Norton & Company, 2002, 235 pp.

Emergence: The Connected Lives of Ants, Brains, Cities, and Software
by Steven Johnson
New York: Scribner, 2001, 288 pp.

Small Worlds: The Dynamics of Networks between Order and Randomness
by Duncan J. Watts
Princeton: Princeton University Press, 1999, xvi, 262 pp.

¶1:22 Driving home from Riverhead, I passed a sign, "Entering the town of Southampton." The road was going through a wood, and the trees before the sign and after were very much the same. There was no line except a line somewhere upon maps and surveyor's charts. Yet, from one side to the other, all sorts of things differ – tax rates and where one pays them, the schools children attend, who puts out fires, which ambulance will respond to an emergency, whether marketers seeking affluent customers are likely to call. Such invisible lines, fraught with practical consequences, are ubiquitous. Such constructs that create boundaries and areas deeply structure the way people in the modern era have come to organize their lives, particularly throughout advanced, highly rationalized cultures. The modern era began with great journeys of exploration circumnavigating the globe, making clear that the human habitat consisted of large surfaces of land, bounded by the oceans. Modernity has been the epoch of the mapmakers, and modern history one in which the maps have been filled in, boundaries drawn and fought over, and the whole surface of the earth possessed and spoken for by humanity.

¶2:22 This history was a vast effort that has profoundly possessed the human consciousness. Who one is and what one has; how one speaks and why one works; how one dresses, drinks, and drives: all and much else are functions of the particular bordered areas one happens to inhabit. Once upon a time, political states, insofar as one could speak of them at all, were accoutrements of dynasties, loosely coupled to definite areas. Times changed. Modern history has increasingly linked the state with a stable, contiguous area through external conflicts over borders and internal consolidations of power. Nationalities, which flagrantly intermixed in the real world, have been drawn and pushed to fit within those same apportioned boundaries, creating the modern nation-state. Societies, less well-defined entities, nevertheless suffuse distinct areas, calling forth diverse surveys whereby academics, advertisers, and political pollsters avidly divine dispositions, hoping for advantage in their quests for tenure, market share, and votes. Economies, too, existed within explicit areas, at least until they went global, and even now, each area still has the coin of its realm and national, state, and local authorities generate most economic indicators – Gross *National* Product and the like – creating world-wide a Babel of statistical sets. Determinations of authority, jurisdiction, and entitlement pertain to a specific territory, and territories come in plentiful types – state, country, county, parish, land, region, province, district, township, locality, neighborhood, section, zone, vicinity, part, quarter: areas all.

¶3:22 Metaphorically, the construction of areas extends into many matters where boundaries on a surface really make no sense at all. We have a spatial metaphor for knowledge and scholarship, speaking of subject matter *areas* and the *boundaries* between disciplines. People pursue all sorts of activities within their *fields* of specialization and their *domains* of expertise, working their *territories* while *fencing off* competition. We speak of the *frontiers* of science and the *coverage* of news. An author will *survey* a subject. A person *centers* his or her interests. The concept of *limit* has extended its diverse meanings far beyond the limits of its original sense, a border beyond which it was unsafe to venture. Metaphors of bounded areas on the surface of the land provide tools of thought, both diverse and powerful. And where these are wanting, addition of a third dimension yields metaphors of volumes, as in spheres of interest, high culture, and a tight fit. If we try to situate an aspect of life in order to hold it consciously in thought, we almost always do it by assigning it a place within some spatial conception or metaphor.

¶4:22 Such spatial modes of thinking have built up over the past 500 years and powerfully organize practical life. They are, nevertheless, at least in substantial part, historically contingent. Mental mapping is not the only way to organize experience. For instance, over the past fifty years or so, networks, as distinct from areas, have been gaining greatly in their relevance to thought and experience. Thinking about things with respect to a network leads to reasoning quite different from thinking with respect to areas. With an area, things are either *in* the area or *out* of it, *inside* or *outside*. With a network, something is either *on* the network or *off* it. Networks do not have clear boundaries; they make and lose links, cohere and degrade, according to principles different from those that govern the populating of areas. If alternative constructs of experience come to displace area-based constructs in the post-modern world, those alternative constructs will very likely have the concept of networks as a key component.

¶5:22 Starting 150 years ago with the growth of railroads, networks have become progressively prominent in daily life. Since the advent of the railroad and its close ally, the telegraph, almost all of the deeply transformative technologies have been powerful networks – the web of roads upon the land; the hub and spokes of air travel; the incredible shuffling of shipping containers around the world by boat, train, and truck; the humming grids striding everywhere distributing electricity; the broadcast networks of radio and television, along with the chains of movie theaters for entertainment; the intricate switching systems for telecommunications; the prodigious managerial networks controlling commercial production and distribution; the ebbs and flows of global finance; capped by the network of networks – the Internet and the World Wide Web. Recently, a fast-growing science of networks and study of concomitant phenomena of self-organization are providing potent new ways to understand these linking systems that knit contemporary activity into a global filigree of multifarious interaction.

¶6:22 Educators should attend closely to the emerging science of networks, for it has many important implications for their work. *Linked* by Albert-László Barabási and *Nexus* by Mark Buchanan provide two useful entry points. Both are remarkably similar in length, heft, and tone, with both concentrating on how the science of networks developed over the past decade or so and the implications it has for issues of economics, politics, health, and the environment. Barabási is one of the major contributors to the emerging field and *Linked* is remarkable as a lucid, engaging introduction for the general reader by a specialist. Buchanan is a professional science writer of stature and his *Nexus* is an equally lucid introduction, slightly more disinterested in his presentation. Barabási conveys the basic science a bit more fully than Buchanan does, and the notes to Barabási's book are by far the fuller of the two. But overall, both books are strikingly similar, covering the same ground in largely the same way, with both working as a clear, well-structured introduction to important intellectual resources.

¶7:22 In an abstract sense, networks arise whenever there are links joining nodes. A link can be as passive as a simple line between two points, a set of which comprises a graph as that is understood in graph theory. In the real world, however, links tend to be more active than a simple line and nodes bear more substantial properties than do abstract points. For instance, one can think of a network within a chemical soup, with the nodes being the diverse molecules and the links being the numerous reactions joining and breaking the molecules apart. Innumerable different networks form within the world of real experience. With respect to each, we can often describe a network, thinking of it as a system, as the sum of potentially interacting nodes within it, and we can then study the states of the network by describing the actual interactions that are taking place at any time within the system. Thus the telephone system, a huge network, comprises the linkages between all the interconnected phones and appliances, and at any instant, the state of the system consists in the buzz of conversations between different parties calling one another by phone, fax, modem, or what-have-you. The science of networks studies the properties of networks, abstractly described, and researches their real-world characteristics, comparing these to the ideal-types of theory. In this science, an effective network links a very high proportion of potential nodes together and an efficient network maintains a very low degree of separation between its constituent nodes, allowing any one to interact with any other through a limited number of steps.

¶8:22 In theory, two postulated networks set the poles of discussion: random networks and ordered networks. A very simple ordered network may consist of nodes arrayed around the circumference of a circle with each node connected to its immediate neighbors. In such a network, interconnectivity of the nodes is very effective, being complete, but also extremely inefficient, especially for large numbers of nodes, as an interaction between any one and any other must pass between each intervening node, requiring numerous transactions. The degree of separation is far too large. Random networks have characteristics that are more desirable. One constructs a random network from a universe of available nodes by linking pairs of nodes, not according to their proximity, but by selecting each node in a pair at random from the entire set. From trial to trial, the linkage patterns of such random networks will vary infinitely, but the systemic properties of random networks are both constant and interesting. Through an initial stage as one constructs a random network, with only a few pairs of nodes connected to one another, the network is singularly ineffective, yielding a very low possibility of any one node interacting with another. As the number of links between randomly selected nodes increases and the ratio between the number of links and the number of available nodes passes .5, however, the network rather suddenly coheres, in what seems to be a change of phase, and a large cluster of interlinked nodes emerges, with the remarkable property of constituting a small world where all the nodes have remarkably low degrees of separation. As a result, interactions between millions, even billions of nodes in a random network that has passed its critical state need traverse only a handful of links. The random network thus exhibits both effectiveness and efficiency, linking in a few steps vast numbers of nodes.

¶9:22 Random networks are fascinating, but alas they seem very unlikely to occur in actual experience, for linkages between real nodes happen, not at random, but under constraints. These constraints produce networks that grow in patterns that are neither random nor ordered. The reason is simple. Real networks occur, not through intellectual acts of mathematical definition, but through the dynamics of growth and development, maintenance and degeneration. Within the real world, proximity is a common constraint. For instance, with computers, it is easier to create a local area network than a wide area one, and with people, a circle of friends more often than not live near each other and highly interconnect, each knowing the others. Under the sway of proximity, real world networks might easily fall into a system of many small worlds in the literal sense in which small groups functioned in intimate interconnection, isolated from any others. In actual experience, small-world networks that link immense numbers of nodes with a low degree of separation, requiring a mere handful of steps for one node to interact with another, come about through the development of weak links and hubs. Weak links jump from one isolated cluster to another, which might otherwise connect only through a very large number of intermediate steps. Hubs are nodes that have unusually large numbers of links leading in and out, raising the efficiency of the networks. In the social world, for instance, a weak link may be a distant acquaintance or relative who lives far away and can serve as a conduit between two separate social clusters. A hub might be that friend who has an extraordinary number of contacts and thrives on putting people together. Weak links and hubs enable networks, which might break narrowly into poorly coupled clusters under the constraints of the real world, to develop nevertheless into very large small worlds. With weak links and hubs, real-world networks can approximate the ideal properties of random networks, joining vast numbers of nodes through a system with very low degrees of separation.

¶10:22 Ideas about the characteristics and formation of networks are new and fast emerging. The unusual degree of similarity between *Linked* and *Nexus* probably arises because both rest on a small number of recent scientific contributions, increasing the probability of convergent interpretations. In particular, *Small Worlds: The Dynamics of Networks between Order and Randomness* by Duncan J. Watts looms large behind both as predecessor and significant source. Watts book is quite extraordinary, showing (among other things) what an exemplary dissertation should be for doctoral students in search of inspiration. Watts found and followed a problem, in the process carrying himself from theoretical and applied mechanics to sociology. *Small Worlds* reports his inquiries, tersely showing a broad range of practical implications as he economically presents his reasoning and equations for defining, exploring, and explaining small world networks, ones that prove to be both effective and efficient. Watts does not spare the technicalities, opening the niche for *Linked* and *Nexus*, but the non-specialist willing to read through Watts' equations in an effort to grasp the reasoning behind them, will find the experience challenging, yet rewarding. Key to the dynamics of small-world networks is the change of phase that occurs rapidly as shortcuts bring isolated clusters of links into full interaction.[1]

¶11:22 Situating the emerging science of networks more generally, it links to rapidly developing studies of complexity and chaos theory, neural nets, cellular automata, and self-organizing systems. Key contributions to the science of networks come from mathematics, sociology, and physics. Advances in the study of complexity, neural nets, and cellular automata cluster somewhat in computer science, represented by the recent tome of Stephen Wolfram,[2] and those in the study of self-organizing systems in biology and ecology, represented well by the work of Stuart Kauffman and the Santa Fe Institute.[3] Steven Johnson's *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* is an introductory reflection on a range of such developments. Johnson brings together a somewhat greater diversity of ideas than do Barabási or Buchanan, but Johnson's grounding in the relevant science is not as authoritative. *Emergence* is a good example of what we might call exploratory journalism by an adventurous author. It provides a useful complement to *Linked* and *Nexus*, drawing added attention to diverse examples of self-organizing development.

¶12:22 For the educator, the growing understanding of self-organized, emergent development is of great importance. Education is an area in which the science of networks may prove extremely helpful, but there is a great deal of further development of the field before educators can apply it to their work with confidence. It is almost as if the study of self-organized systems is still itself a sparsely filled network that has not

1 While both Barabási and Buchanan cite Watts' work, particularly as reported through Watts and Strogatz, "Collective Dynamics of 'Small-World' Networks," *Nature*, 393(1998):440-42, neither cites *Small Worlds*, although both would seem to have learned much from it.
2 Stephen Wolfram. *A New Kind of Science*. (Champaign, IL: Wolfram Media, Ine, 2002).
3 See Stuart A. Kauffman, *At Home in the Universe: The Search for Laws of Self-Organization and Complexity* (New York: Oxford University Press, 1995). "Self-Organizing Systems (SOS) FAQ," maintained for the comp.theory.self-org-sys USENET Newsgroup, is an excellent resouree (http://www.calresco.org/sos/sosfaq.htm -- July 20, 2002).

quite reached its critical stage of emergent coherence with several clusters of interaction but many potentials not yet on the nascent network. But it is getting there and it may be useful to anticipate some possible applications, for such anticipations may help lead ensuing, systematic effort to fruitful questions.

¶13:22 Traditionally, scholars have conducted most educational research, somewhat uneasily, using causal models of inquiry. By and large, a causal inquiry starts by defining one or more bounded groups as the object of study. By enumeration or sampling, the researcher then describes the distribution of characteristics shared among members of the group and studies how different causal variables, set to work through an intervention, may affect the distributions of observed characteristics. The results, whether or not they are statistically significant, ultimately register as an incremental shift, for better or for worse, on the bell-curve distributions of the characteristics shared by the members of the bounded group in question. The peak rises or falls, the range widens or narrows, and most importantly, the mean moves to left or right along a scale of desirability. The changes are incremental; the characteristics are constant.

¶14:22 Many educators have long felt uneasy about the standard causal model of inquiry because they sense that the important developments in education are not manifest in incremental changes in the characteristics distributed among the members of an arbitrarily bounded group. Instead, they observe that powerful educational experience occurs through transformative changes in the course of persons' lives. Such transformations appear to be frequent in educational experience. What happens when the infant's capacities of perception rather suddenly cohere? How did the toddler in that short week or so in the whole of a life get the hang of standing and using gravity to step forward, a skill nearly every human masters? How is it that all children, in a quick move from babbling, start to speak, virtually untutored? Acquiring a skill is not incremental, step-by-step; rather it seems to happen to the youth almost by surprise as she goes from a plaintive "can't do it" to an expansive "hey, I can." What are the incremental causes to a sense of conviction or a commitment to a friend? What is the learning sequence leading to the youth's emerging sense of wonder, to the teenager's fast-forming, ever-changing tastes?

¶15:22 These and many other examples encountered consistently in human development and education seem resistant to explanation through incremental change and appear to be akin to phase transitions where something changes from one state to another, as when solid ice melts to liquid water and water boils off as gaseous steam. The science of networks and the study of self-organizing systems offer models of inquiry that center on phase transitions, using powerful mathematical tools that are quite different from those describing the bell-curve frequencies observed in bounded groups. With self-organized systems, their powerful features arise, not by making a managed sequence of specific connections, step by required step, but by passing certain thresholds of connection-making, after which the coherent system of skills, capacities, and understandings emerges, functionally ready for sustained development. Explanations of the phase transitions sustained by self-organized systems need to be holistic, not reductionist. Any sequence of connections, on reaching the critical threshold, will self-organize into a new state and the important properties of the state are properties of the state as a whole, and not the particular sequence of steps through which its component parts entered into the new state.

¶16:22 Life is full of phase transitions, emergent processes, suggestive of the dynamics of self-organizing networks. Let us hypothesize how we might understand educational transitions, which seem resistant to causal explanation, as the emergence of self-organized networks within the person. In doing so, we might note as an aside, appropriate for expansion at some other occasion, that the science of networks may help clarify the long vexatious mind-body problem. The mind-body problem is fundamentally an in-out dilemma. We can perhaps solve it by shifting the venue for the problem from one where things are in or out of something, an extended body, to one where the experience occurs on or through something, an emergent network. If having a mind and being conscious is an attribute of certain kinds of self-organized networks, what requires explanation is not the locus of the mind in the body, but how a certain kind of network has the capacity for consciousness on the one hand, and how that network can organize itself on the neurobiological capacities of the living person. To be sure, these embed in a physical volume, the brain and the body, but it is not the spatial characteristics that seem essential to the living network.[4] Consider a simple analogue. The picture on the TV is not *in* the set, but it appears to be on the screen because the whole complex network of broadcast and reception is turned on and active. The picture is there because that is the state which is *on* on the network. So too it may be meaningless to say that the mind is in the body because mind is an emergent, self-organizing network that functions on the living, human body with its complex neuro-motor potentialities. My system is "on," sustaining a network that after a couple years of development organized itself in such a way that consciousness emerged as an attribute of its operation.

¶17:22 We are in this way postulating that life eventuates, conducts itself, on and through emergent networks. The typology and organization of these networks is manifold and complicated, running from the dynamics of cell division to the development of all the obtuse specialties of human culture. In the processes of development and education, each person, we hypothesize, forms a many-sided system of interconnected, self-organized networks, all serving together, for apprehending and acting in the world. Each person lives day in and day out through a bundle of kinetic capacities, an acquired emotional make-up, intellectual abilities, skills and cultural interests, all engaged with matters, from the significant to the minor, in a complex habitat. Let us simplify and postulate how a typical component of this many-sided, self-organized network might emerge. Such components emerge, with unique particulars, for every person. The emergence happens through an educational change of state as a student has made enough linkages of a certain type – be they kinetic, perceptual, emotional, rational, cultural, what-have-you as the case may be – to pass the critical point for a self-organized network. It then emerges as a functioning capacity, uniquely

4 Watts in *Small Worlds* repeatedly finds that relational networks, on which simple on-off states characterize links, have the most interesting network properties in comparison to spatial networks, which act as small-worlds only when the operative distance of links can span something close to the maximum distance spanned by the whole network. Even in the "real world," many networks, for instance defining the contagion of disease, act digitally in that someone either does or does not become infected.

configured, that the student can thereafter use as an element in his or her self-directed development.

¶18:22 Educators and parents are familiar with the outward results of such self-organization in learned capacities, components of each person's personhood. The child will seem to plug along on one or another plateau of learning or growth and then suddenly, to everyone's surprise, a new interest or capacity swiftly coheres and emerges as a self-sustaining acquisition. Once it emerges, the effectiveness of an acquired network lies not in the specific sequence of its component connections, but in the degree and character of interconnectedness of the whole. When the student attains enough linked nodes, with the reach of those extended by working weak links and hubs, a small-world network forms, both effective and efficient, one capable of growing greatly to include innumerable further features while preserving a low degree of separation between them. Once it initiates itself, given opportunities, it will continue to grow, with its characteristic hubs becoming fuller and its connections between component clusters diversifying.

¶19:22 If we understand a person's cultural acquirements as a complicated intellectual network formed by multiple steps of self-organization, we must not conclude that positive educational efforts are unimportant. Rather the growing understanding of how networks emerge helps to identify potentially crucial ways that educators can assist the process. First, the science of networks suggests that providing a rich diversity of intellectual stimuli and resources is more important than trying to restrict or channel intellectual development to ensure that someone will end up with a certain preferred intellectual repertoire. The educator should provide the student with a culturally intensive environment, offering the student many chances to acquire information, ideas, and skills, the potential nodes in his or her network of acquired culture. Formed in an intensive milieu, the network of cultural acquirements likely to self-organize for the student may take a relatively long time to reach its critical point, but then it will emerge full and many-sided.

¶20:22 Second, the science of networks indicates that hubs providing concentrations of efficient links are very important. An intellectual or social-emotional network should be an efficient, small world that a person can use as a whole by maintaining its components with a low degree of separation among them. Hence, the educator should concentrate his attention on nurturing effective organizing ideas and principles, the really powerful concepts in the culture, which will allow the student to develop supple, sure patterns of thought. The importance of hubs probably suggests that formal instruction concentrating on the thorough mastery of key ideas, seminal principles, will have greater use in the self-organization of a well-formed mind than will instruction that maximizes vague coverage of assorted ideas.

¶21:22 Third, the science of networks suggests, too, that weak links allow a network to hold a broad copiousness together efficiently, providing capacities to develop an economical breadth of interest and capacity. Consequently, the educator should provide for diversity in the student's surroundings, a diversity of ideas, skills, and persons. A highly separate education, via seclusion in the home or segregation within the group, is unlikely to provide good opportunity for forming the weak links that allow for mobility, mental or social. Because connections across mental, emotional, and social distance permit powerful networks to self-organize effectively, we can see better why poverty, intellectually fatuous instruction, and cultural isolation lead to limited educational results. The science of networks provides a powerful rationale for multicultural education, for ensuring that teachers have the fullest possible command of their subjects, and for providing all children with full access to the resources of the culture and with many-sided stimuli to exploit that access.

¶22:22 In the large sense, challenging environments that are rich in stimulus, connecting principles, and diversities are likely to prove to be the great pedagogical enablers suggested by the science of networks. As early as Plato, theorists have argued that education is not a process of putting knowledge into the empty vessel of the person. Rather it leads them to develop an inner orientation towards meaningful ideas and aspirations, that is, curiously, in current parlance, turning them on to a chosen way of life. The study of self-organizing systems through the science of networks is fully consistent with traditions of education that consider the student and his or her self-development as the essential agent of humane results.

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