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Regulated Turbulence in Information

"That which is static and repetitive is boring. That which is dynamic and random is confusing. In between lies art."
John Locke (1632–1704)

Introduction

This essay has four parts. The first briefly shows ways in which the physical concepts of turbulence (randomness or entropy, without the hidden simplicity that has recently come to be associated with the word *chaos*) apply to information as well. The second argues that it is worthwhile looking for evidence that turbulence is not simply present, but *regulated* in real systems. The third gives examples of well understood systems and the ways that they regulate turbulence. The fourth contains speculations about the applicability of these ideas to human brain function.

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Turbulence in information flow

Physical turbulence is characterised by unpredictability at many scales, caused by interactions that are strong, long-distance, and varied. It may seem odd to relate this to the world of *information*, with its precise rules and often perfect solutions in many problem domains. However, many information-processing tasks can be solved in disorganised ways (Introna and Whitley 1996). These tasks generally have no single correct outcome, and can be solved using bottom-up collaborative approaches. Disorganised problem-solving works by generating vast numbers of possible solutions, and then judging them in some way, or making them compete with one another (Figure 1). Such methods optimise the *fits* between species and environment, antibodies and epitope, theories and data (Campbell 1974).

Surowiecki (2004) suggests that the *Wisdom of Crowds* arises from sharing of information, cooperation, and coordination of activity. Selection theories, and standard approaches to "wicked problems" (e.g. van Bueren and Koppenjan 2003), all are more general, in that they include the potential usefulness of distortion or of outcomes being novel rather than right. In such cases, B, D, and E tend to be important; whereas in more pre-planned systems, A and C usually predominate.

Such consideration of a wide variety of systems together can shed light on underlying principles: "some scientific theories are representative of types of theories that solve types of problems." (Darden and Cain 1989). More specifically, biological theories based on *selection* have been very successful, particularly in evolution and immunology. However, selection requires the fuel of *diversity*, which has not received the same degree of

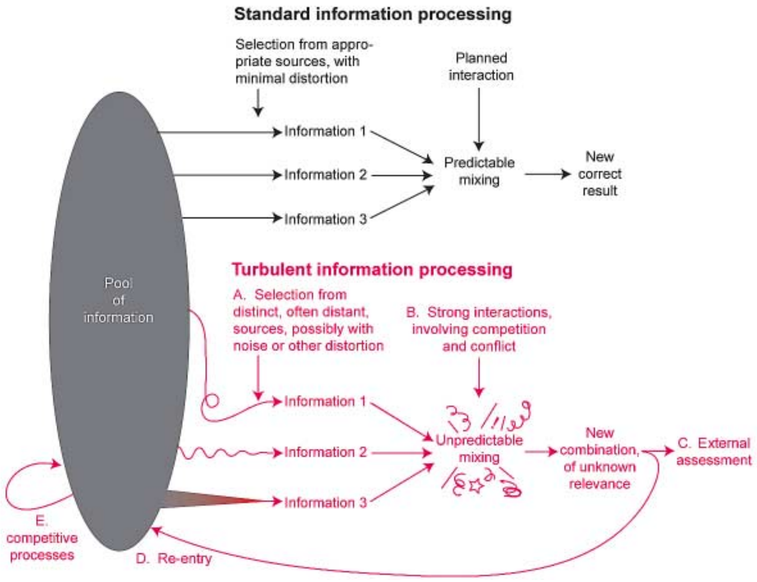

Figure 1. Standard versus turbulent information processing.

attention as selection itself. The same authors assert that "as long as preexisting diversity exists, the details of the mechanism of its production can be omitted from a selection type theory." Similarly disinterested, Campbell (1960; 1974) described "blind variation" as the root of creativity and made a strong case that it is the root of all knowledge. The current essay attempts to address the omission, and show that variation is not completely blind.

Regulation of turbulence

A computer program that prints bank statements cannot cope with unpredictability. If a single bit of information is altered, the statement will probably be useless. The program can be extended to check its data in various ways, and even correct itelf, but it will work best if there is no unpredictability at all. It will certainly not be designed to *introduce* unpredictability.

If we find systems in which unpredictability arises, how can we know whether this is an accident or a useful part of the design? In general, one of the best pieces of evidence for the usefulness of a characteristic is a demonstration that aspects of it would not be expected had it arisen for other reasons such as chance (Andrews et al. 2002). So if randomness occurs in rather specific ways, or is precisely *regulated*, that would constitute evidence that a degree of randomness is useful. The hallmarks of *regulation* are mechanisms to increase and decrease turbulence, and to control the balance between them. These would be quite different from the bank program or, at the other end of the spectrum, from unevolved nature, such as the weather, which produces the maximum entropy possible for the available energy (Whitfield 2005) – a limitation that does not apply directly to information.

When looking for mechanisms that regulate turbulence of *information*, we can be heuristically guided by our understanding of turbulence in *fluids*. Turbulence helps when mixing fluids (Chen 2001), and study of this process has revealed ways of keeping the amount of turbulence within useful limits. The simplest of these involve changing the *strength* and *variety* of interactions, and the *scales* over which they occur (for others see Chen 2001). These factors all have counterparts in information systems that appear to be used to regulate turbulence, i.e. for both increasing and decreasing turbulence (Yang et al. 1995; Chen 2001).

Well-understood examples of regulated information turbulence

Examples 1 & 2 illustrate random *selection*; then 3 to 6 illustrate random *mixing*.

Example 1: Random search methods

Monte Carlo methods involve unpredictable information selection (Fig. 1A). They are brute force methods that do not rely on intelligent planning. Self-avoiding walks are one method used to force exploration. The degree of randomness can be gradually reduced as in simulated annealing.

Example 2: The Oxford English Dictionary

Creation of this massive work, "on historical principles", involved enormous logistical effort. Thousands of volunteers, many with no specialist training, wrote down "unregistered words" and illustrative quotations which they felt illustrated usage, and posted these to Oxford (Winchester 1998). In Oxford, the examples were methodically organised into subcategories and chronological order. It turned out that some of the most useful of the volunteer contributors were also the most unique (Fig. 1A) – i.e. with unusual obsessions, methods, or reading matter – because their contributions overlapped so little with others'. However, their submissions were systematically checked (C).

Example 3: Immune response

Our immune system has evolved to scramble genes randomly on an immense scale (Fig. 1, A,B). This prepares us for challenge by pathogens which select (C) a much smaller number, still in the thousands, of antibodies for proliferation (see Silverstein 2003). Evolution in this case has selected mechanisms for scrambling and amplifying, but not specific sequences of antibody molecule.

Example 4: Evolution

Evolution is the example par excellence of positive change achieved through the selection, mixing, and re-selection (Fig. 1,A,B,D,E) of information – in this case encoded in sequences of DNA. Life has evolved relentlessly in the direction of increased complexity (Szathmary and Smith 1995) except for the simplest creatures (Azevedo et al. 2005). It is clear that evolvability has evolved, increased through the introduction of gene-mixing mechanisms, uncoupling of processes, versatility, compartmentation, redundancy, and long-distance travel – in general, deconstraining effects (Kirschner and Gerhart 1998). A range of genetic mechanisms are used to increase mutations at appropriate times and places (Metzgar and Wills 2000) Constraints on the speed of evolution are the difficulty (cost) of improving on current designs, and the group fitness benefits of long lives. Cultural units (memes) evolve analogously to biological units (Dawkins 1976; though Andersen 2005), but propagate by imitation, and potentially without dilution or regulation.

Example 5: Academic research

In the academic world it is clearly important both to encourage new ideas and to check them rigorously. Selection and mixing of ideas (Fig. 1,A,B) take place in individual staff, whereas peer review for publication (C,D) takes place separately and is required for entry into the pool of published information. Within this pool, ideas compete (E) for readers and citations.

The organisation of education, finance, and above all peer-review, encourage constancy of interests, i.e. low turbulence. Acting in the opposite direction are seminars, sabbaticals, centres for advanced study, and boredom. Some of these are regulated by political perceptions of need; others by social forces intrinsic to science (Hull 1990; see Fig. 2).

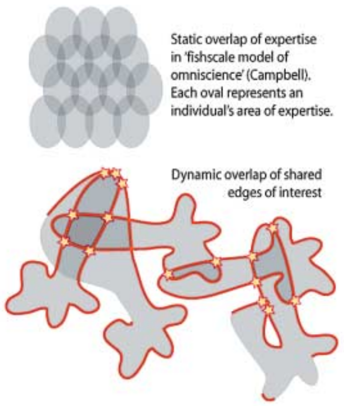

Figure 2. Overlaps between academics.
a: Donald Campbell (1969) viewed interdisciplinarity as the overlap of individuals' static areas of knowledge.
b: Individuals' current interests (red) are often at the borders of their expertise (grey). Current interests have small, dynamic areas of overlap (stars) which may be more important than overlap of expertise in allowing innovation.

Example 6: Wikipedia

Wikipedia is an online encyclopedia which can be freely updated by the public. This is a great novelty, and produces a lot of information mixing. There are 670,000 articles in the English language edition, viewed by 10 million people each day. It was hoped that erroneous contributions would be rapidly corrected by the many people making corrections, inexorably improving Wikipedia until it far surpassed any printed encyclopedia. Hence one of its slogans is "Out of mediocrity excellence."

Wikipedia turns out to be ideal for collecting simple, objective, noncontentious, voluminous information, e.g. soap opera plotlines, or towns in Alabama. The many viewers rapidly correct mistakes in such lists. However, Wikipedia may be fundamentally unsuited to academic subjects, most of which have different vocabularies, mindsets or values from the public: Wikipedia cannot instruct at all levels of understanding simultaneously. It also struggles in fields with strong divergent minority views (e.g. sex or religion), because the content of articles either oscillates or becomes an average of views, weighted by enthusiasm for making the change. Other problems are vandalism, and the gradual degradation of organisation or balance within expertly written articles. There are proposals to reduce this turbulence by introducing voting; or encouraging multiple strong viewpoints to be represented; or using more citations; or making it more difficult to delete (revert) other people's contributions, unless they are lower in a hierarchy of reliability.

Is regulated information turbulence found in human brains?

Like previous selectionist accounts, this has "plausibility by analogy", but must remain vague given our limited knowledge of brain function (Darden & Cain 1989).

It is well known that the initial wiring of the brain contains a great deal of randomness, and that this becomes organised, first topographically and later by learning. At the level of overall brain organisation, though, the idea of randomness is less accepted, because neurophysiologists' success in assigning functions to some of the cells in some brain areas (e.g. sensory and motor cortices) has seemed to suggest that Lashley's equipotentiality (Lashley 1950) was relevant only in lower animals – and also because of a predisposition to believe that we are organised.

But EEGs certainly look random, and their synchronisation in states such as sleep appears regulated. In broad outline the brain's structure is well suited to perform all the functions shown in Figure 1 (A-E). Cortical areas produce different assessments or associations (A); these then interact, or compete, via association fibres (B) and further association takes place (D,E). The basal ganglia sample the resulting patterns, selecting (C) those which have produced the best outcomes in the past (Schultz et al. 1997; Redgrave et al. 1999).

It may not be obvious that random processing can play a useful part in solving complicated problems in practical amounts of time. However, many problems (e.g. face-recognition, visual search, categorisation, and motor planning) can be reframed as *optimisations*, for which random solution methods are well-understood (Example 1). The study of optimal solutions, or fits, is important in many areas of learning (Campbell 1974) including machine learning and simple, phylogenetically old, forms of learning. A recent example is the linking of temporal difference (TD) learning to dopamine (Schultz et al. 1997). TD learning is ideally suited to guide the optimal selection of actions from a large, diverse, set of predictors (Wolpert and Tumer 1999).

Our thinking may be more turbulent than is commonly supposed. For example, magical ideas are much more common after childhood than is usually supposed (Bolton et al. 2002) . As another example, people tend to be intrigued by contradictions, surprises, or problems that they partially understand. A *drive for turbulence* (similar to *novelty drive, curiosity drive, dopamine appetite)* offers one explanation for this (see Hebb 1955; Williams and Taylor 2004). High or low drive is a lifelong trait of some people. The drive is increased temporarily by strongly positive events (causing excitement) and reduced by tiredness, stimulants, or in times of stress (McReynolds 1971), when a reduction in associations can usefully improve reliability (Hanoch and Vitouch 2004).

Variability of behaviour appears to be trainable (Neuringer 2004) but is also increased by low reward probability (Gharib et al. 2004). This suggests there are at least two mechanisms regulating the variability of behaviour (see Williams and Taylor 2004). Serotonin may have a role in these: it has intra-cortical connections that appear capable of gating long-range connections between cortical areas (Park 1998). The fluid analogy suggests that these will modulate turbulence, and indeed serotonin appears to regulate cognitive flexibility (Clarke et al. 2004).

Symbol processing

Problems that cannot be treated as optimisations (such as language or mathematics) appear to be learned by symbolic rule-following mechanisms that have become learned by initially disorganised networks (Omori et al. 1999; Chalup and Blair 2003), perhaps located in prefrontal cortex

(Rougier et al. 2005). This is consistent with what we know of the evolutionary accumulation of learning methods (Moore 2004) and the centrality of symbols in our thinking (Olds 2000). Long-distance interactions between cortical areas, and the "small-world" property, appear to have increased during evolution, in parallel with cognitive ability (Johansson and Rehn 2005). Adding even a few of these long-distance connections to a network radically increases the number of different associations that can be made (Ball 2004). This may have been an important contributor to our ability to use symbols and then language (see Jackendoff 1999). Support for this comes from the finding that language is encoded in connections between the speech area of cortex and distant cortical areas, rather than being in the speech area itself (Pulvermuller 2005).

Brains are equipped with several features that increase the power of random search. These include the use of learned and unlearned heuristics; the pre-processing of sensory information; and the use of multiple, semantically distant, metrics in cortex (e.g. Wood and Grafman 2003). The distinct metrics also increase the likelihood of disagreement between brain areas (Freeman 1991) or between predictions.

The proposal – that information mixing needs regulation – suggests that this relatively recently evolved symbolic system will also have such regulation. One candidate is the phenomenon of cognitive dissonance, i.e. conflict between ideas in a person (Festinger 1957), which is a key psychological function increasing our willingness to change existing ideas, hence reducing *intra*personal conflict. Our drive to reduce the *experience of internal disagreement* – and our ability to *remember* conflicting views – are both demonstrated by our difficulty, even with some effort, in perceiving the picture at right as partly an old woman and partly a young one.

Mental disorders

Most attempts to link psychiatry to turbulence or chaos have been psychodynamic; this section addresses the information processing that is taking place. The premise of regulated turbulence suggests the possibility of dividing disorders into hyper- and hypo- turbulent, and those that have nothing to do with turbulence. This is not to underestimate the impairment and suffering caused by psychiatric disorders.

Hebephrenic thought disorder in schizophrenia produces an incomprehensible jumble of words and sentences (Sims 2003) which may turn out to be caused by *excessive* turbulence. Delusional *systems* in schizophrenia are quite different, growing like islands of certainty, perhaps because disordered thought prevents their being properly monitored and discarded. People with attention-deficit hyperactivity disorder (ADHD) have highly variable behaviour, and Figure 1 suggests that this may be caused by increased variability in either data selection or mixing. Supportive evidence comes from functional brain scans showing that they use more widespread areas of their brains to solve problems (Durston et al. 2003).

Depression, and anxiety-related disorders such as post-traumatic stress disorder and obsessive-compulsive disorder, involve repetitive or stuck thinking, and it may be that underlying this is an *inadequacy* of turbulence of ideas (see Yang et al. 1995). Negative emotion focuses attention on single, simple factors (Luce et al. 1997), contributing to the persistence of these illnesses; this over-focus may be one target of antidepressant medication.

Anorexia and dissociative disorders are even more persistent; more culturally determined; and show poor response to medication. This is consistent with the possibility that a component of these disorders is embedded as information within the categorising system mentioned above. Hence Multiple Personality Disorder has been described as “forged by an artisan rather than by nature” (McHugh and Putnam 1995). This suggestion receives some support from taxonometric findings (based on symptom scores) that, unlike depression and anxiety, these symptoms are not on a continuum in the population (Haslam 2003).

The value of unpredictable behaviour to the group.

Is it possible that erratic behaviour, in a minority, helps the group as a whole? Information uncovered by an individual, even by his errors, can be useful to other people who learn from it. So in some cases his errors and risk-taking may have the effect of unintentional altruism. (Fig. 3; see Williams and Taylor 2005 for more detailed discussion). This is similar to Example 2.

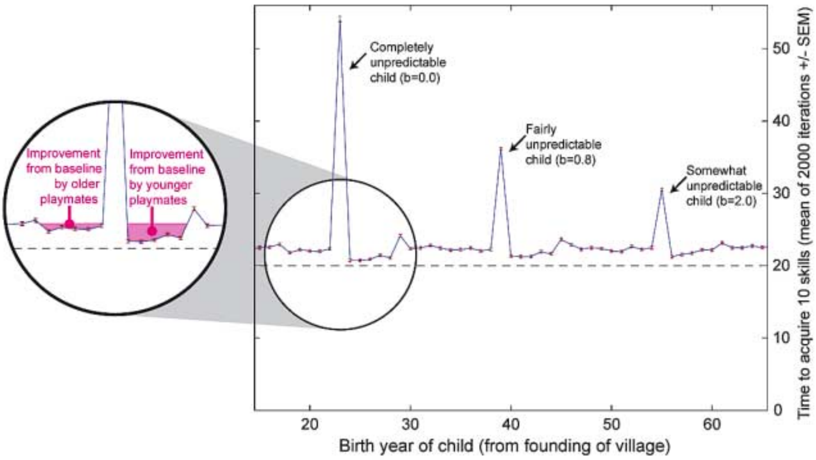

Figure 3. Simulation of maturing individuals in a village: Social skills acquisition during development. Each point represents a simulated child, with the first-born at the left. All the simulated children are identical apart from their level of predictability (brittleness, b). All but 3 of the children are highly predictable, with brittleness b=8. The three high peaks in the graph represent the slow maturation of three unpredictable children who take extra time to acquire skills (brittleness values b shown next to their peaks). These three children’s unpredictability produces some useful vicarious lessons for their playmates, particularly the younger ones. The benefit to playmates increases as the individual’s unpredictability increases.

Conclusions

Evolution, working in a haphazard, brute force way, using conflict and adaptability, in contexts of staggering parallelism and diversity, equipped us to solve many problems in similarly *disorganised* ways. This is because large-scale unpredictability can help organisms that are seeking *relatively good* answers (i.e. useful or better than others; satisficing) rather than a special case of this, *the right* answer. The distinction between large-scale unpredictable populations, and predictable populations of any scale, is not in predictability, since sufficiently large populations of turbulent processors can produce any required degree of predictability (Frost and Stirling 2003). Instead, the difference is that unplanned information mixing produces a "richness of flexibility, and a cornucopia of new opportunities" (Chen 2001; see also Dietterich 1997).

	A. Selection of information	B. Mixing of information	C. External assessment	D. Re-entry into pool	E.Competition
Random search	random selection by algorithm	rule-based (e.g maximum wins)	rule-based	(typically no re-entry)	(typically no reentry)
Evolution	mating	random assortment of genes	fitness in environment	offspring reproduce	survival
Immune (molecular)	random selection of V,J,D genes	splicing	by presentation of pathogens	(no re-entry)	(no re-entry)
Cognition; Mental illness	various sources & metrics; excess control by turbulence drive?	turbulence drive; failure or misregulation of drive	primary reinforcers	immediate	best predictors, cognitive dissonance
Informational altruism	unpredictable behaviour reveals information	information is shared within social group	?	simple updating of previous information	(none)
Wikipedia	self-selection of contributors	from assorted contributors	limited – by administrators	immediate reeditability	by persuasion

Table 1. Characteristics of information mixing systems. A-E refer to Figure 1.

This essay has illustrated some ways in which variation can be created (see Table 1), and in which variability can be regulated. Inter-individual differences in information-processing are likely to play an increasing role in our views of the brain, evolution, and society (Szathmary and Smith 1995), from which they have been largely excluded by the averaging inherent in diagnostic systems and most experimental techniques. Statistics based on populations, and simulations of homogeneous populations (e.g. neural nets; cellular automata (Weiss 2003)), have major limitations in studying neuropsychological functions of populations that show strongly multidimensional differences in these functions. Simulations of heterogeneous competing agents, acting without higher-level control, is likely to produce breakthroughs at cellular, regional, cognitive, and evolutionary levels. Clinically, the possibility that dysregulation of information turbulence underlies some brain disorders suggests new directions for research, particularly in drug mechanisms and concepts of disorder.

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