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The Potential for a Self-organizing System

Applying Cybernetics to Air Traffic Management and the Growing Congestion Problem

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Abstract

The United States air traffic control and flow management system affords a good example of how and why systems theory and cybernetics is valuable. The system is congested, and it will become more congested as global air traffic increases. Flights can no longer rely on the current airspace resources, as they are frequently unavailable. These include runways, airways, radars, air traffic controllers, and, now – due to augmented security precautions – airspace. To date, no system solution has been put forth. The paper uses the air traffic flow management (TFM) system as an example of how to use a formal vocabulary to approach systems problems. Following an outline of *methods*, the paper shows how the methods can be applied to the very complex TFM system problem. We refer to *methods* in the descriptive sense, for the system problems under consideration are well beyond the use of a formal system of axioms, theorems, and proofs. Propositions and variables are extremely helpful in surveying the landscape; but real-world problem-solving demands real-world imagination and common language, as well as mathematical intuition. So our approach recommends elements of formality *and* description. The *methods* unify three of the fundamental models that have evolved from mathematics and logic, computing, model and systems theory, and neuro-science. These are, in relation, (a) finite state automata, to formally describe values and therefore potential meaning; (b) loops, which give rise to memory and the potential for awareness and future; and (c) intent, which, as a result of inherent neural, natural, and artificial looping, allows us to plan for the probable and improbable future, based on past personal and scientific experiences, and then know it. This triad, we believe, is sufficient to encapsulate most systems independent of their technologies and techniques. In this paper, we apply them to the TFM system.

Résumé

Le système de gestion de commande et d'écoulement de trafic aérien des Etats-Unis est un bon exemple de la façon dont et pourquoi la cybernétique et la théorie des systèmes sont valables. Le système est encombré, et il deviendra davantage encombré par suite des augmentations globales de trafic aérien. Les vols ne peuvent plus se fonder sur les ressources courantes de l'espace aérien car elles sont fréquemment indisponibles. Celles-ci incluent des pistes, voies aériennes, radars, aiguilleurs du ciel, et, maintenant - en raison des précautions augmentées de sécurité –l'espace lui-même. Jusqu'ici, aucune solution de système n'a été mise en avant. Le papier prend en exemple le système de la gestion d'écoulement de traffic aérien (TFM) et la façon d'employer un vocabulaire formel pour approcher des problèmes de systèmes. Après un survol des méthodes, le papier montre comment les méthodes peuvent être appliquées au problème du système très complexe de TFM. Nous nous référons à des méthodes dans le sens descriptif, pour les problèmes de système dont l'étude va bien au delà de l'utilisation d'un système formel d'axiomes, théorèmes et preuves. Les propositions et les variables sont extrêmement utiles pour décrire le paysage ; mais la résolution des problèmes réels exige l'imagination réelle et le langage commun, aussi bien que

l'intuition mathématique. Ainsi notre approche fait appel à des éléments de formels et de descriptifs. Les méthodes unifient trois des modèles fondamentaux qui ont évolué en mathématiques et en logique, calcul, modèles et théorie des systèmes, et neurologie. Ces modèles sont en relation : (a) automates finis d'état, pour décrire formellement des valeurs et donc la signification potentielle ; (b) boucles, ce qui est à la base de la mémoire et du potentiel pour la conscience et le futur ; et (c) intention, liée à l'état neuronal inherent et s'appuyant sur des boucles artificielles qui nous permettent de projeter un avenir probable et improbable, basé sur des expériences personnelles et scientifiques. Nous croyons que cette triade est suffisante pour encapsuler la plupart des systèmes indépendamment de leurs technologies et techniques. Dans cet article, nous les appliquons au système de TFM.

Introduction

Three elements are presented here to establish a systems science vocabulary for problem solving*: intent*, *loops*, and *states* (or values). The least understood is the first. Intention, or intent, is subjective and the consequence of many elements: looming large is our drive to obey cultural rules - as instantiated in language, education, and organizations; emotions; reflex-reaction; and moral judgments. Cultural rules, in particular, as they circumscribe politics, economics, and religious beliefs, impute a marked bias to our considerations for action. Although man and machines today interact seemingly without boundaries, man is not a machine.

Our paper uses the concept of probability as a basis for analysis of *intent*. Considerable work has been done in the field of probability to align it more fully with logic: notably, Bayes's theorems and the principle of maximum entropy. Bayesian methods in particular are predicated on inference, which requires data, and thus embraces the concept of likelihood. So, in systems, it is imperative that the actions and outcomes of the system in question be analyzed. Old (and recent) data, when viewed under the light of new ideas can yield productive insights.

Loops are fundamental to thought and artificial systems. Without them, neither man nor his machines would have memory. An action many times reviewed breeds at least the potential for insight. Here the roots of logic again become evident. In his first incompleteness theorem, Gödel was motivated, in part, by self-referential propositions and logical paradoxes, such as the truth of "This very sentence is false." By substituting numbers for propositions and variables, he cultivated the idea of an algorithm, that is, a recursive function, which calculates in a finite number of steps, values derived from their functional history. Turing, in mapping the second theorem to an alternate proof, used this idea of looping to further the issue: Is it provable? Is it decidable? Is it computable? So, we can only assert intent after looping; as reflection is required for it.

Finite state automata derive immediately from Turing's theorems. So the connection between intent, looping, and semantics is close. The finite state machine is an abstraction of a computer, with intent secreted behind the set of order pairs of ordered pairs that inscribe it. The intent was ascribed to a computer according to Turing, and the computer was an English schoolboy. The result, as we now witness every day, is computation of values, which, as they meld with our everyday actions and natural events, deliver a fuller, but more complex, meaning.

The Example: The US air traffic flow management system's objective is to observe traffic flow by airspace throughout the flying day. The FAA established a center dedicated to monitoring and, in the case of potential congestion, alerting the airlines and the regional FAA control facilities, that they might adjust routes and/or altitudes in flight, or hold planes on the ground. These actions are taken based upon flight data that is inaccurate and, in many cases, incorrect and inconsistent. The problem is marked by limited resources, notably runways, airways, and a plethora of restricted airspace. The system' chief emergent quality (1) is uncertainty and unpredictability, due mostly to weather. Flights rarely follow their planned routes; even the best planning, based upon historical airline schedules and actual routes flown, is readily defeated by the exigencies of the real world. Very few commercial flights are on time; hours-long delays abound.

The TFM system is marked by outcroppings of automation. Hundreds of humans intervene on behalf of a single flight as it networks across the country. No one sees the same situation in the same way, including the pilots. The system's behavior is non-deterministic and nonlinear, due largely to the unpredictability of weather, but also because of the inherent side-effects of recursion in altering a single flight's trajectory over the entire set of flights. Purely discrete methods (e.g., calculating fix times of arrival) cannot account for the uncertainty. To date in the US, there is no closed-loop, real-time model operating as part of the system. To quote Robert Rosen (2), the US system has the *potential* to be a third-order cybernetic system; such a system "contains a predictive model of itself and of its environment that allows it to change state at an instant in accord with the model's predictions pertaining to a latter instant."

Formalizing the Methods

The object then is to capture, as accurately and precisely as possible, the entire system, not its parts, but its characteristics over the whole, and its emergent properties. We must include decision making, or intent, as well as primary cybernetic forms, namely looping, and state-machines, wherein values are produced that hold the potential for meaning. We must first study the system and the data it produces and identify its problem or problems. Systems questions arise: For example, we can capture in formal propositions the transformation of an aircraft's spherical coordinates to a stereographic plane, but how do these values relate to the larger human values of safety and security? What is important about the loops in a system and how should we fortify them, augment them, delete them, or create them? How do we capture the relationship of values to organizations as events pass through them? If we use the prescribed methods as thought-tools, and not as formulae, we can construct an intellectual framework for the system; diligent analysis will suffice, making synthesis unnecessary, as solutions should become obvious.

Intent can be reasonably apprehended as a probability, based upon experiential data. Its *a priori* makeup is indecisive. So, as we use it in systems theory, intent must rest upon empirical evidence and the opportunity to learn from the past. Probability is needed when deductive reasoning cannot be used; i.e., when the necessary information is not available.

As it applies to the TFM system, qualifying and quantifying intent, or intention, relies on analysis of decisions made and their *implied* consequences. Here there are limitations: causation is too strong for inference. In the TFM system, studies of historical, actual data suggest that holding departing planes on the ground will relieve congestion at the arrival airports – the idea being that

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this attenuates arrivals, spreading them over a longer time horizon. When the FAA uses ground delays however, they often have a negative or no effect on arrival congestion.

We find no better formal model of intent than Bayes (3). Although it is sometimes overstated, the element of likelihood that inhabits non-frequentist probabilities is useful in systems thinking, simply because it relies on actual (posterior) performance. Bayes's Theorem relates the probability of a hypothesis (H) conditional on a given body of empirical data (E), $\mathbf{P}_E(H)$, to the inverse probability of the data conditional on the hypothesis, $\mathbf{P}_H(E)$.

$$P_E(H) = [P(H)/P(E)]\, P_H(E), \text{ where } x_i\ \varepsilon\ \{E\}$$

Loops: we begin with neural loops. From neuro-science we suspect that they are degenerative and multi-axial. Different paths yield identical results; and primary loops are themselves looped: thus memory, awareness, and a concept of future, from which we have derived the ideas of probability and uncertainty. Natural loops are basic to organic and inorganic configurations. In cybernetics, the most interesting is the social loop – as humans communicate among themselves through learning and language. In the TFM system, language and communications are decisive. Here the foundations are enormous. So we acknowledge the linguists, anthropologists, psychologists, logicians, and analytical philosophers who have mined and continue to mine this field.

Computing loops are derived from recursion theory, emanating from Gödel proofs. In practice, the effective procedure, or algorithmic loop is a sequence of iterative steps, the vast majority of which are written by programmers who have never heard of Kurt Gödel. Formally, recursion is described by the mathematician Stephen Kleene (4) as
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$$f(0)(x) = x;\ f(n+1)(x) = f(f(n)(x))$$

Loops evidence themselves in all systems, although their presence may be subtle. Our work is to identify the loops of interest. One of the fundamental problems in the TFM system is that it is incomplete in this sense: the actual system is not closed under a predictive model of itself in real-time. There is no immediate feed-back between intent and the current values of the system (where, for examples, the planes are). Thus, the studies performed on the effects of ground delays are at times contradictory and inconclusive; not because the studies themselves are incomplete – they are well-defined and -documented; but because the system under study is incoherent.

Finite state automata have been described in great detail by mathematicians and computer scientists: Minsky, for example (5). They are useful in modeling the behavior of simple and complex machines, systems organizations, and all combinations thereof, because they consider memory. The figure below shows the form of the state machine. As a tool, it mirrors the Turing machine, and the auto-mechanical transformation of values. The state machine itself embeds looping, as historical values participate in the calculation of new values, which in turn deepen the history. Whether the mind works this way is a matter of some speculation (of course one would need to consider the entire history of species rooted in our brains to approach any verisimilitude), but systems and organizations – especially those heavily populated with automation – can be modeled under this pattern without argument.

Modeling the TFM system as a state machine at the highest common-sense level of abstraction is straightforward. Axiomatically (in common language), the *invariant (I)* that must hold is this: *each flight flies the shortest, equitable route, such that the set of flights and the set of restricted air-and-ground space cannot intersect, optimizing on (National Airspace System – NAS) resources.* The term "shortest, equitable" means that airline business rules, fuel consumption, and the natural environment must all be taken into consideration. The NAS resources include not just runways, airways, navigation and communications, but also the workload of the air traffic controllers – who are currently *over*-worked because of the laborious step by step use of clearances that march the planes along airways (in the US, this is referred to as the "board game").

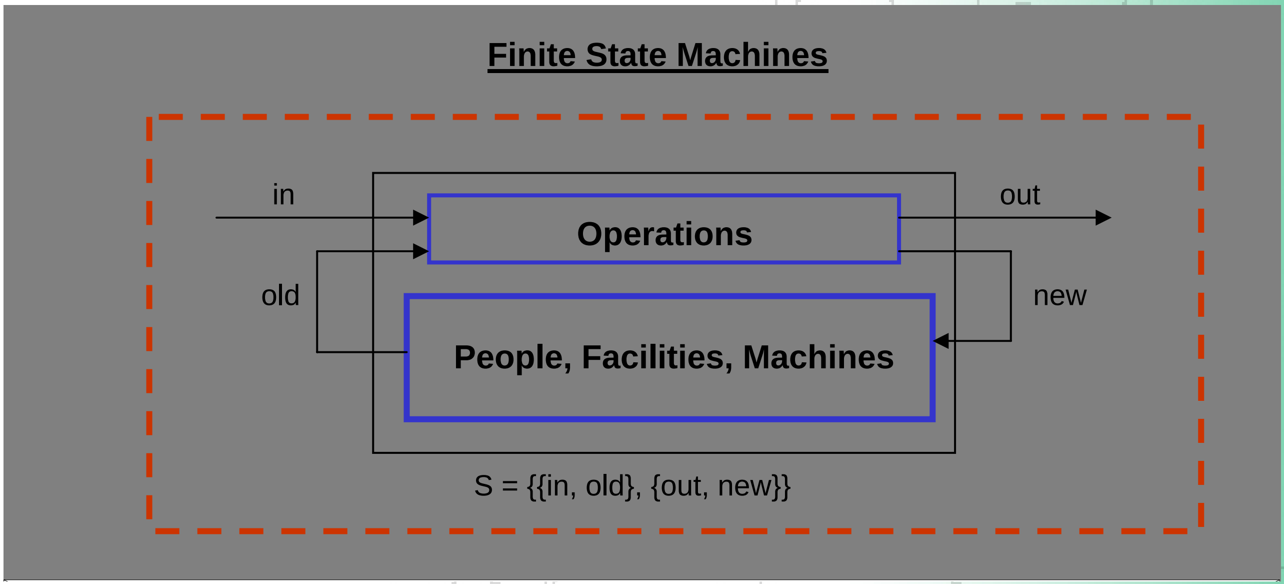

Figure 1. The Use of Finite State Machines to Formalize Values and their Meanings

Our formalism given below, from Minsky (5), is this:

$$x_{out}(t+1) = f(x_{old\_state}(t), x_{in}(t) \quad \textit{and} \quad x_{new\_state}(t+1) = g(x_{old\_state}(t), x_{in}(t)$$

The output value at t+1 is a function of the input and old state at time t; the new state at time t+1 is a (different) function of the same set of ordered pairs.

Applying the Methods

Our analysis of TFM is based upon the objectives of the system, its context, and its current set of functions, as well as its structure, and size. TFM combines the flight-by-flight air traffic control (ATC) operations – regionally assuring separation – with the NAS-wide airspace flow control mission to monitor and alleviate congestion. Our systems analysis has identified four activities, which interact continually: (i) data capture of the regional flight plans and tracks; (ii) communications to system operators – the TFM Hub in Virginia, controllers, pilots, airlines; (iii) [at the Hub] re-ordering the situation from flight by flight to airspace and diagnosing the congestion; and (iv) feedback. The most difficult issue is (iii), as the set of airspace and its imbedded set of aircraft must be treated in its entirety to assure that *the invariant (I)* described above is met. (Altering one flight immediately remaps the sets creating a new problem; all flight-airspace sets must be treated simultaneously.) Using our systems framework, we will apply the use of intent, loops, and state machines to the overall system and specifically to (iii) and (iv). (i) and (ii) can be solved using current tele-computing technology and techniques.

First we discuss *intent*. Looking at the highest practical level, we can characterize the system according to its primary objectives: safety and economics. People and cargo must fly safely and the passengers and institutions that transport cargo wish to fly as efficiently as possible. Our analysis of the data enables us to hypothesize this: *the system operates safely, if and only if (iff) it operates inefficiently*. The question then is Can the system operate *efficiently and safely*? It can if we consider weakening supply and demand. Let's explain that!

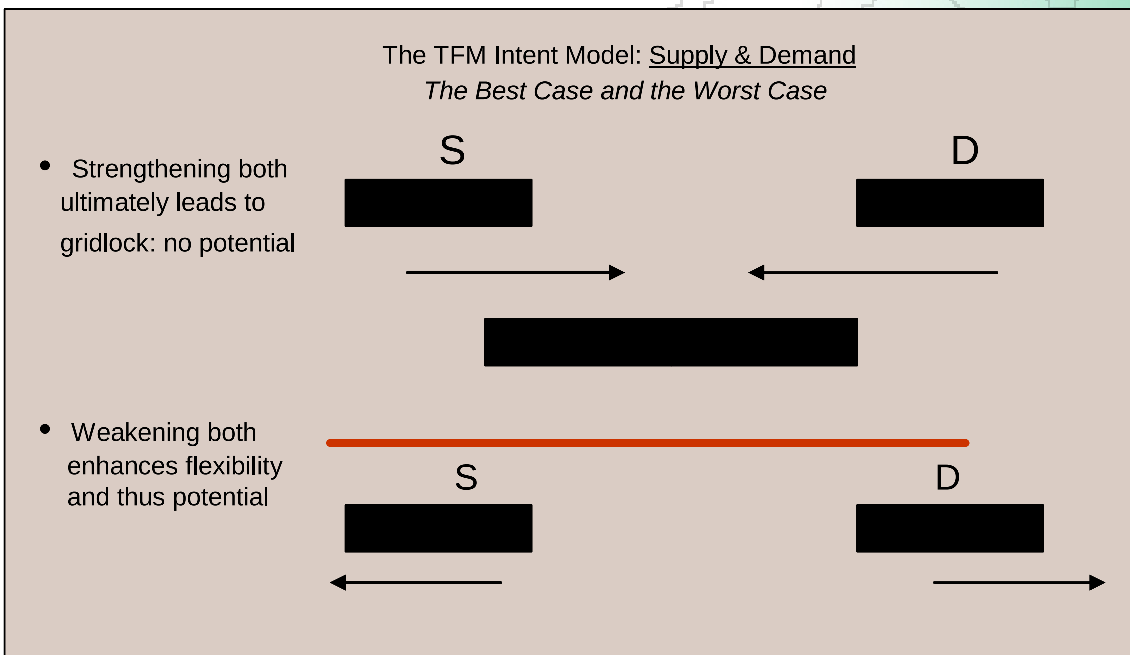

Figure 2. Intent Modeled in Terms of Economics

The supply of the TFM system is represented by the fixed resources, airports, runways, airways, airline constraints (each major airline flies through its preferred hubs to optimize on crew changes, ticket prices, fuel and other free market parameters), and the very rigid control system (the board game) that relies on decades-old ground navigation aids rather than say satellite navigation and off-route flying. Mathematically, this set of parameters is strong in the extreme. The demand side is equally strong. Americans wish to fly whenever they want to fly. Even the high prices charged for tickets are no deterrent, as 90% of air travel is business travel, whether people or cargo, and corporations foot the bill. Their costs for travel are then passed on.

Our recommendation is to conduct Bayesian studies on how one might weaken both supply *and* demand, as that would provide the most elasticity, especially in light of projected growth (from 650,000,000 passengers a year to double that number by 2015). Hypothetically, our intuition, and that of many experts, is to (a) weaken demand by applying service level agreements to customers, such that they would be guaranteed price-performance over a long term, as constrained by the available resources – in a manner similar to the service-on-demand/quality of service agreements of telecommunications carriers and service providers; and (b) weaken supply constraints by encouraging air carriers and the FAA to support satellite navigation and "free flight," and, further, to renovate (further than has been done) the FAA, so that it performs as a commercial service provider and operates as a performance-based organization (PBO).

The significance of using propositional-probabilistic logic under Bayesian rules is this: There is sufficient data in transportation and communications systems world-wide that could be used to test hypotheses that our intuition and engineering judgment suggest might work. Using the data in a systematic way to assert solutions is essential. Making arguments without "proof" will surely fail. Although the data is proprietary, we have used both actual and simulated data in our analysis, in concert with other studies using Bayesian methods, so we can validate the necessity, of *a posteriori* analysis and reasoning.

The significance of *loops* in the system under study is patent. The problem at hand is not that loops do not exist, they do; it is that they are ineffective. To solve this problem requires a through understanding of the cybernetics of the system. Refer to the figure below as a starting point. The loop between the potential and the actual in today's systems is virtually useless, as aircraft intent and predictive weather are maintained separate from the real-time, real world system, and, in a sense, referred to as one might consult an almanac. For example, no high-availability, synchronous, secure network connects the en route and terminal control centers, the airline offices, and the TFM Hub. Thus, as controllers (assuring separation), pilots (flying the aircraft), airlines (meeting flight deadlines), and traffic managers (insuring that capacity meets demand) try to collaborate, they do so under enormous latency. Further, in collaborating, each is looking at a different view of the system, over different time horizons, at different times.

When an adjustment must be made, say, to amend a flight's altitude or to hold a flight on the ground, the system never achieves coherency. Aircraft traveling at hundreds of knots and weather fronts arising in seconds do not wait for geographically-dispersed operators, with different views and second-order objectives, using largely manual procedures. Simply stated, the adjustment is always made to a system state that no longer exists, and it is made by operators who never had a complete picture of it in the first place.

We suggest that a real-time model of the airspace and all of its mobile elements be projected probabilistically so that all stakeholders may be able to apprehend and contemplate the systems as it is and as it will be in its entirety. Imagine pilots, controllers, airline offices, and traffic managers having immediate access to the NAS, at any interval in time, describing the current trajectory of all controlled flights and weather, projected over some parameterized time horizon, influenced by probabilities of occurrence. Completeness is achieved in the dialectical: the actual system and its model operate as thesis and antithesis, with the feedback resulting in synthesis. The contradictions inherent in the actual system (a planned route is compromised by a sudden military event or warm weather turbulence) are projected by the model, which presents a new *intent* – as though the near-present system were the planned system of long ago.

From the looping between the model and the actual system of pilots, controllers, automation, et al, a synthesis emerges from their disagreement, which then surfaces new

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contradictions that are then reconciled as the process renews. The continuous feedback is the nub of self-organization.

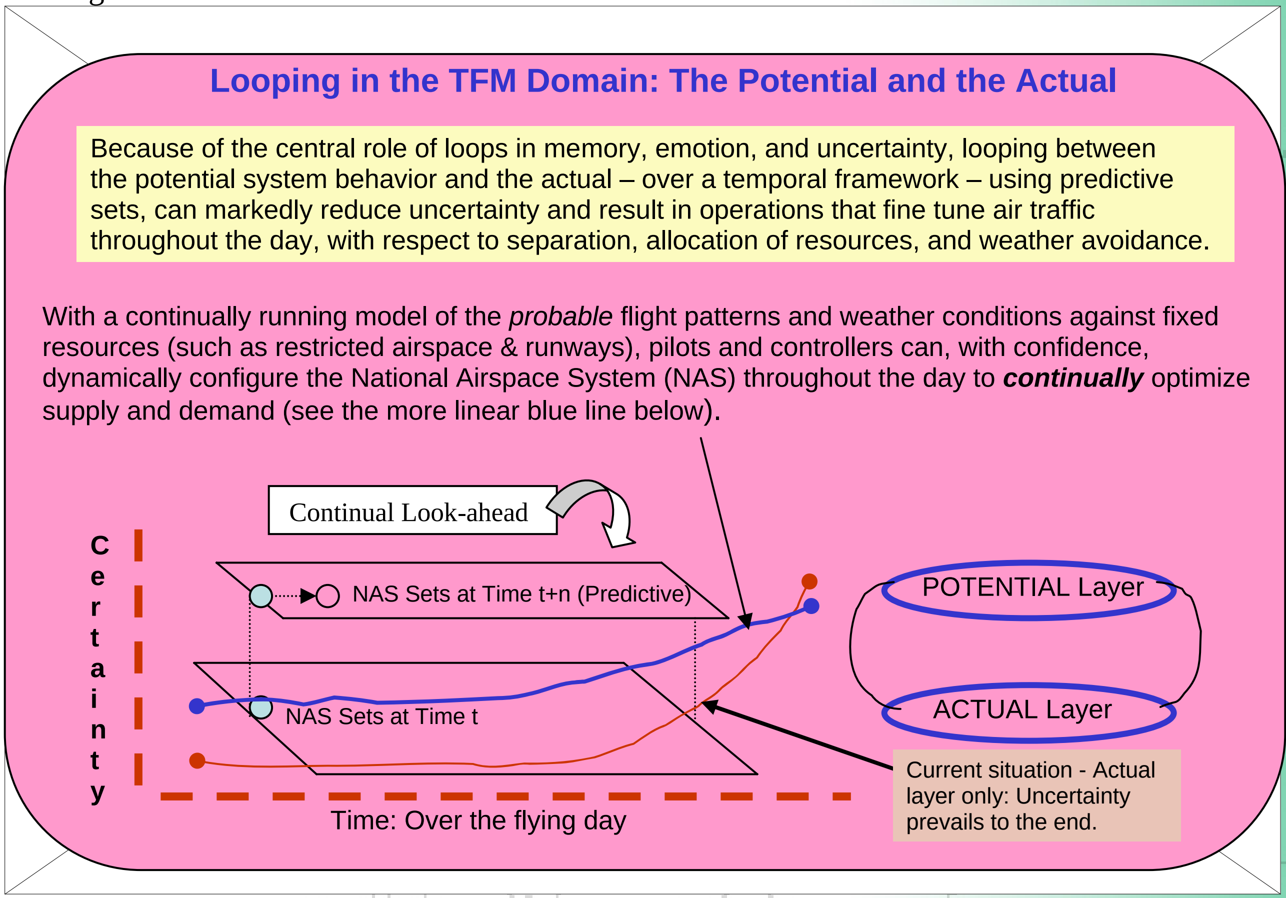

Figure 3. Closing the TFM system with a Model of Itself

The TFM system, with its own dialectical, finds its own equilibrium, with minimal human intervention, through the interplay of positive and negative feedback cycles. Positive feedback increases the number of potential configurations; negative feedback stabilizes configurations.

We can use probabilities to probe the future of weather and flight trajectories. We can also use them to resolve the potential conflicts these predictions evince. Here artificial intelligence is of enormous help. Neural networks, for example, allow us to project patterns under a learning rule, so that the system can self-organize according to plan. At the TFM Hub, then, an optimizer runs continually, evaluating the potential and the actual in real time.

The optimizer converts aircraft and weather to polygons and sets of polygons that are amenable to extended set processing and neural networking. The learning rule establishes the outcome according to the invariant we have described above and runs until it discovers the best solution. It records the steps required. These then are mapped to clearances that, in the future perfect sense, would keep the planes apart, and help them fly the most favorable route. This must be done on the entire set in order to avoid the recursion problem of compromising the whole airspace situation by altering single flight's trajectory. (Thus, the algorithm is of the form (x)*f*({x}): for all x over the set of x.) See the figure below. Suppose we wish to organize moving balls, with impediments (weather, restricted airspace), so that, in 2 hours they are realigned, as the algorithm *probabilistically* tries thousands of strategies, oscillating through some learning rule, until it achieves the result. Then it chooses the strategy with the optimum adjustments.

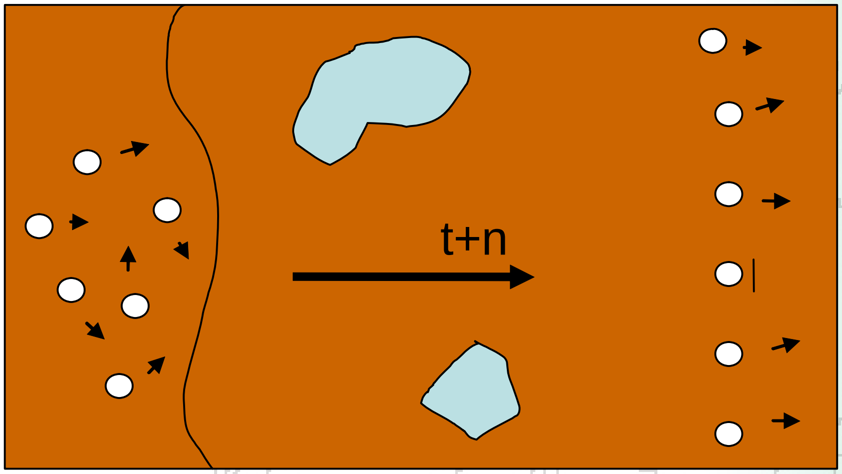

Figure 4. A Neural Network Optimizing on Intent over the Entire Set

The process is continual; in real time, feeding back potential adjustments to air traffic controllers and airlines, which will enable them to choose a proper course of action. Eventually, this cybernetic loop can be fully automated. In the near-term, we recommend that the planned course of action be translated to a form of *objectives* that allow humans in the loop to consider the actions, and manage them under their own intention. For example, an output might be "Clear Flight AS420 to flight level 240 over fix LAX at 1310 local time." This is one of a set of potential actions that the optimizer, in neural network vernacular, recommends in human-understandable text. (Objectives, rather than commands, allow humans to further adjudicate the constraints of safety and business rules and interpret the interplay of positive and negative feedback cycles.)

The optimizer is an example of a state-machine, in that it learns from the previous states in conjunction with the latest input. But this is not the only use for the finite state machine in understanding and improving the TFM system problem. As Beer (6) uses actuators and attenuators in his diagnosis of viable systems, we can take advantage of the state machine properties to evaluate the various organizations that participate in this (now) hypothetically closed system. Referring back to Figure 1, the various organizations involved in the ATC-TFM process can be diagnosed with respect to the values that are imported and exported, and the "values" they "own," in terms of information, hard assets, objectives, cash, business rules, and organizational structure and policy.

Our analysis shows that using such a tool will surface the complex and inbred patterns of the organizations under study. For example, the FAA controllers are union-run and, historically, have been given veto power over technological advances, as these may disturb their well-worn habits. The airlines are profit-driven and are often in financial difficulty. Contractors wax and wane, as air traffic control is not a dependably strong market. Hundreds of millions of dollars are poured into research and development with fully-funded organizations, but technology transfer lags well behind today's rapidly changing technologies. It is beyond the scope of this paper to design the organizational state machines, but we have used such artifacts in our field work.

Conclusions

The TFM system is not unique. It is biologic, surely in the sense that it was created, and is run and populated by humans, but also because it approximates the behavior of organic phenomena: its stability depends on the environment, it requires continual support, it is dynamical, and it changes, as it adapts, or strives to adapt, to local circumstances. The system embraces and assimilates politics, economics, and social constructs, as it must navigate the real world and natural systems. Further, the system is highly symbolic; much of it is artificial, as radars, computers, and a wealth of digital and analog machines blend and reconcile with human activity.

We have introduced methods, grounded in mathematical and logical concepts, that we believe can encapsulate large, complex systems, to understand them and to help solve their fundamental problems. We hope this is a start towards a calculus of complexity, as the tools allow us to express with some rigor the past, present, and future of a system, or a system of systems, and its emergent properties. With the example system, the unpredictable TFM system, our goal is this: to show how systems theory and its methods can foster self-organization and self-regulation, not as adjuncts, but as foundations, for a system, that, over time, may well otherwise collapse.

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