Complexity Science Applications to Dynamic Trajectory Management

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Abstract

Systems thinking, in the context of complex adaptive systems, provides a framework for dynamic trajectory management in a NextGen-based National Airspace System (NAS). The tools developed under this framework would draw their power from agent-based technologies, applied through computationally efficient combinatorial mathematics. The approach would transform air traffic control from managing individual aircraft behaviors to managing systemic behavior of air traffic in the NAS. A system built on the approach would provide the ability to know when regions of airspace approach being "full," that is, having non-viable local solution space for optimizing trajectories in advance. The capability would also allow for optimization of domain-specific parameters such as airspace capacity and business case metrics. An approach for evaluation of such a system with humans-in-the-loop is suggested.

Introduction

The U.S. Airspace and NextGen

The U.S. airspace is approaching a crisis point where mere operational inefficiency is edging closer to compromising safety, increasing costs to users and the FAA, and producing excess greenhouse gases. Current traffic is straining the existing system of air traffic control to the breaking point, and future traffic promises to introduce a whole new set of challenges for which the present system has insufficient provisions. The current system of traffic management has protocols dating back to World War II, a time when all of the "smarts" were on the ground (radar and radio beacons) and aircraft had a radio, an altimeter, a compass, and (to borrow from novelist J. Levine) a wing and a prayer.

In the intervening years, technologies have evolved on many relevant fronts. The synergy of these technological advances is now at the point where the operation of the U.S. airspace can be fundamentally re-thought. The stated goal of the FAA and JPDO's NextGen program follows: *"NextGen moves away from legacy ground-based technologies to a new and more dynamic satellite-based technology…. These new capabilities and the highly interdependent technologies that support them will change the way the system operates, reduce congestion, and improve the passenger experience"* (1). Key technologies include ADS-B (Automatic Dependent Surveillance Broadcast), SWIM (System Wide Information Management), Performance-Based Air Traffic management, and NextGen Data Communications.

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Systems Thinking

System Thinking

- Massive interdependencies
- Computational efficiencies
- Role of simulation

In addition to technological advances, systems thinking about the U.S. air transportation system offers an approach to accounting for the interdependence of all of the players in the game. Systems thinking has been around for decades, from the cybernetics of the 1950s (2) to the general systems theory of the 60s and 70s (3, 4, 5). In the field of systems thinking, just as in the case of the national airspace, practical advance is tied to technological innovation. Many of the systems science ideas put forth in preceding decades did not achieve fruition or application until the 1990s and beyond because comprehensive understanding of those systems required ubiquitous access to powerful computation.

This requirement was met in the development of the desktop computer with associated languages and operating systems capable of building, simulating, and interacting with complex systems. Quantitative advances (in faster, smaller, cheaper, and more flexible computation) eventually resulted in qualitative advancements, namely in powerful and flexible simulation. Thus, simulation became a third category of scientific inquiry, complementing (even completing) the traditional roles of theory and experimentation. For instance, aircraft testing that used to happen in wind tunnels or structures laboratories now more often than not, happens inside of computer simulations. This maturation means that airspace architecture and procedures developments can now be evaluated and implemented by applying the advances from systems thinking to the challenges of dynamic air traffic management.

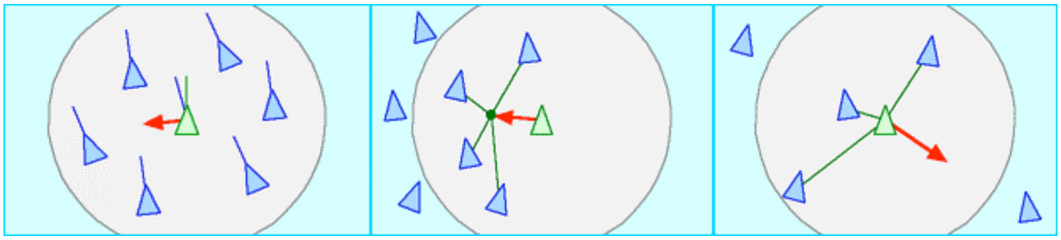
Complex Adaptive Systems

Complex Adaptive Systems

- Biological Systems Origins
- Agent-based Technology
- Genetic, learning behaviors

The latest incarnation of systems science is often called CAS (Complex Adaptive Systems) and is generally associated with the Santa Fe Institute (SFI) (6, 7, 8). Scientists at the SFI and elsewhere have studied systems as diverse as ecological communities, immune system response, stock markets, automobile traffic, and crime waves. CAS takes its lead from biological systems and generates, among other things, computational methodologies for simulating and controlling man-made systems. These natural and human systems are tied together by at least the three following critical commonalities: Agency, Open Systems, and Adaptation.

Agency: CAS are characterized by many "agents"— entities capable of decision making, utilizing some degree of autonomy. In general, these agents do not have access to the entire state of the system, but rather are constrained to use data that is local and relevant. These agents may be stock traders, flocking birds (9), ants, flight path trajectories, or even aircraft with or without pilots. Figure 1 depicts the simple but well-designed rules that produce the amazingly realistic and fluid motion.



Alignment: steer towards the average heading of local flockmates

Cohesion: steer to move toward the average position of local flockmates

Separation: steer to avoid crowding local flockmates

Figure 1. – Example of Agent Rules (C. Reynolds, 1989 [9])

Open Systems: CAS may gain or lose agents and even types of agents because of their internal dynamics, such as individuals in an ecosystem being born or dying, generating the emergence or extinction of entire species. This openness prevents many real-world complex systems from being treated by traditional analytical techniques borrowed from statistical physics and economics that were built using the more tractable mathematics of closed systems. These traditional methods produced such triumphs as the ideal gas law and general equilibrium theory in economics. These methods are not suitable since many modern systems are open and cannot be considered in isolation from their surroundings.

Adaptation: Agents are able to "learn" and modify their behavior over time in response to their histories so as to optimize their behavior. This ability generally means a higher probability of survival in natural systems and more cost-effective behavior in engineered systems. They are also able to adapt to disturbances and disruptions in the system, since most natural systems are perpetually "noisy" and error-prone.

What can CAS do for the U.S. air transportation system?

Coping with Complexity, Past

The U.S. airspace is facing a "complexity catastrophe" engendered by too many moving parts, too many constraints, and too many required decisions. Even though it is

Complexity in Airspace

- An over-constrained system
- Managed by simplification
- "Complexity catastrophe"

technically possible to know the state of the entire airspace at a given time, it is computationally overwhelming to use this quantity of information in a practical way. For example, the complexity of computing the next course of action for each aircraft increases exponentially with the number of aircraft and rapidly becomes intractable. Therefore, any solution is going to require reducing the effective complexity of the system.

The current ATC system does exactly that. It reduces complexity by introducing constraints to the system such as the division of airspace into sectors, fixed airways between VOR stations, vertical and horizontal separation protocols, and procedural separation. This constrained system has worked well for decades, but at the cost of reduced efficiency and capacity. This system is now reaching the end of its effectiveness, largely because systems that were previously treated as separable (for instance cruise trajectory management and tower-controlled air traffic management near large airports) are now becoming coupled due to increasing traffic density. As a result, the current methods of reducing complexity will no longer work efficiently.

Learning from the Internet

Lessons from the Internet

- **Robustness**
- **Redundancy**
- **Efficiency**

The U.S. airspace may be able to take a page from the Internet's playbook in terms of managing complexity while introducing fewer efficiency-killing constraints. Instead of behaving like a huge information packet-switching network, the airspace is comprised of a person- and cargo-switching network, and the "packets" are aircraft (10). The Internet was originally designed to be robust and fail-safe, particularly in the event of a nuclear war. It has achieved this goal by incorporating redundancy and distributed control. It works reasonably efficiently because it has local rules (routing protocols) that, when implemented by many routers in parallel, produce an aggregate systemic result that is fairly optimal in terms of resource utilization (11). Since these rules were well designed, the Internet continues to operate effectively even though it has far outgrown its original defense system ambitions in terms of size, complexity, and diversity of applications.

The U.S. airspace, by contrast, is much more "high-touch" than the Internet, requiring more human intervention to keep operating safely. To keep the workload for air traffic controllers manageable, this human intervention component will need to be reduced, as it has been with the Internet. Granted, aircraft are more important than the average bit of information in data packets, and unlike bits of information cannot be split up, copied at will, sent via various routes, and reassembled at their destination. Nonetheless, several key concepts, in particular, Agency, Redundancy, and Adaptation, are transferable:

Agency: Packets contain meta-information, including, for example, destination. The information packets then interact with local rules (routers) to get where they are going without having to refer to a central authority. This approach dramatically reduces computational complexity and dependency.

Redundancy: The Internet works even when some of its parts do not because it has multiple pathways for an information packet. The interaction of local routing rules with multiple pathways generates a large number of optional future paths at each decision point, making the system as a whole robust.

Adaptation: The local rules for routing information allow the system to adapt to disturbance, such as routers or transmission lines being down. Adaptation is essential to robustness, along with redundancy and agency.

Coping with Complexity, Future

At the highest level, maintaining a manageable workload for air traffic controllers is going to require offloading some of their work in an intelligent fashion. A good place for this work to go is in the air, distributed among the aircraft in the airspace by giving them the information and the capability to act as agents on their own behalf. If this is done properly, the capacity, safety margin, and efficiency of use of the airspace can all be markedly increased while increasing the robustness and adaptability of the ATC system.

Implementing this transition properly requires the appropriate hardware and software for aircraft not only to know each current position and anticipated trajectory, but also to have some notion of other aircrafts' *intent.* In this context, *intent* means not only knowing where an aircraft is going, but knowing its negotiation protocols and preference structure for interacting with other aircraft that may perturb its path. To achieve this capability electronically will require a formal computational language by which aircraft can negotiate with each other on the use of the airspace as well as default and fail-safe backups. As a naïve example of an agent-based protocol, the following communication between two aircraft could occur: "If projected conflict is positive, we both perturb our trajectories by 10 degrees left and recompute possible conflict until possible conflict is negative." A complete communication protocol would include sophisticated conflict resolution (and other) protocols in a dynamic trajectory optimization system.

Coping with Complexity in NextGen

Designing such protocols will require a full-spectrum scientific approach that accounts for the business case parameters in NextGen trajectory management, in addition to the airspace capacity and aircraft operations components. That approach starts with theoretical considerations of system stability and mechanism design, evolves through

Dynamic Trajectory Management
- Capacity expansion
- Business parameter inclusion
- New fleet manager role

computational testing and simulation in increasingly sophisticated and realistic model environments, and eventually produces a set of protocols that are ready to be tested in a simulation environment with humans in the loop, such as in the NASA Air Traffic Operations Laboratory (ATOL).

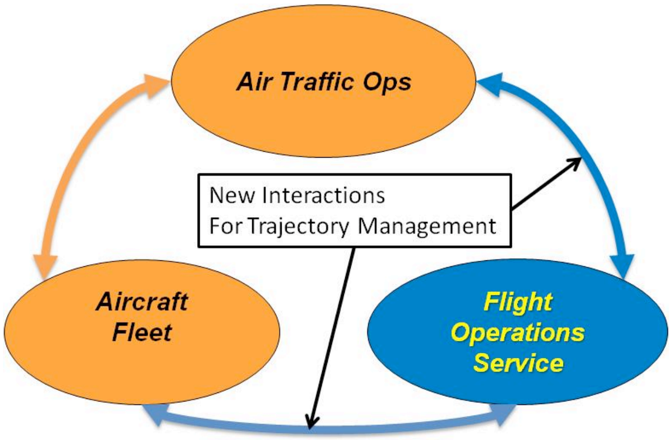


Figure 2. – Integrated NextGen Trajectory Management System

Figure 2 illustrates the integration of the dispatch function (for example, at a Flight Operations Service center or Airline Operations Center [AOC]) in the process of NextGen trajectory management. Traditional airspace procedures research has typically accounted for two of the possible three components in a NextGen system. In addition to the aircraft fleet/pilot and ATC controller interactions, an approach to NextGen trajectory management could include the dispatch function to integrate the business case parameters into the business of trajectory management. The ultimate goal is flight testing, perhaps using something like volunteer air carriers, university training fleets, and government research aircraft to test and evaluate air traffic scenarios.

Relevant Components of CAS to NextGen Dynamic Trajectory Management

Game theory (12):

Mechanism Design

- Game Rules
- Incentives
- Optimization

Originally developed in the 1940s to model military conflict and economic choice, game theory has modern relevance in the field of mechanism design (13, 14, 15): How does one design local rules of interaction (game rules) so that a larger system composed of subsets of agents interacting with each other by local rules of interaction produces an efficient and robust result for the entire system? Nature is rife with examples. For example, ants in an ant colony are not aware of the state of the entire colony, but their local decisions in foraging and defense behaviors serve to further the colony and optimize its chances to survive and prosper. Another example is the food system in New York

City, which at any one time has only a three-day supply. However, a complex system of commerce and transport markets ensures access to food is uninterrupted all the way from farm to table without micromanagement by a central authority. These system examples serve as metaphors for managing air traffic.

This methodology of aligning local rules and incentives with consequent system behavior would be useful in designing protocols for collision avoidance, separation, and trajectory optimization between pairs or small numbers of aircraft in a local or regional space. The resulting method would simultaneously ensure safe operation, overall system effectiveness, and a level economic/business landscape for all players in the airspace. This is the logical next step beyond creating local rules by which aircraft avoid each other, as is currently the subject of exploratory research (16).

Traffic physics

The science of traffic physics is a new field emerging at the boundary of the study of agent behavior and statistical physics. To date, the science has largely been applied to roadway vehicle dynamics because of the significant societal and financial import. In addition, traffic systems are perceived to be highly suboptimal, and offer ready access to large amounts of data (17, 18). This research has applicability to other many-agent systems in addition to roadways (19). The utility of the science is the ability to define systemic measures that are independent of the particular behaviors of each agent in a traffic system, much as the pressure exerted by a gas on its container is independent of the details of motion of each individual molecule. Analyzing traffic systems is also computationally extensive, another reason why the field is so new. As the Nobel physicist Murray Gell-Mann once said, “Imagine how hard physics would be if particles could think.” Systems of cars or aircraft are essentially thinking particles, serving as evidence of Gell-Mann’s insight.

Physical systems consisting of many particles are often characterized in terms of *phase*, such as liquid, solid, or gaseous. The phase is a property of an entire system, rather than of any of its particular components (molecules, cars, or aircraft). The dependence of systemic properties on a small number of critical parameters can be shown on a phase diagram.

Phase Transitions

- **Metaphors for airspace**
- **Defining “full”**
- **Option viability**

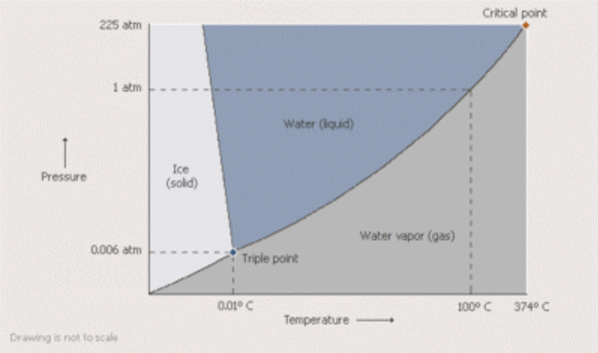


Figure 3. – Phase Diagram for the 3 Phases of Water

As an example, Figure 3 illustrates the three well-known phases for water that are dependent on temperature and pressure. The phase of water can be controlled by adjusting these parameters.

Systems of interacting agents in freeway traffic also have phases that correspond to free-flowing ("liquid") or jammed ("solid") traffic. Traffic also has phases that do not have analogues in physical systems, such as backwards-flowing waves of stalled traffic mixed with moving traffic. Phase diagrams for vehicle traffic look somewhat different than the water phase diagram above because there is one critical parameter (vehicle population density) to adjust instead of two (temperature and pressure). Just as the water molecules obey certain laws (conservation of energy and momentum, equipartition of energy), the traffic "molecules" obey simple laws – attempting to get where they are going as quickly as possible (with an upper limit) and interacting with other vehicles, such as avoiding collisions and following at a safe distance. In vehicle traffic, throughput (or capacity) of a roadway increases with density to a certain point after which a marked decrease is observed; hence, the emergence of a traffic jam.

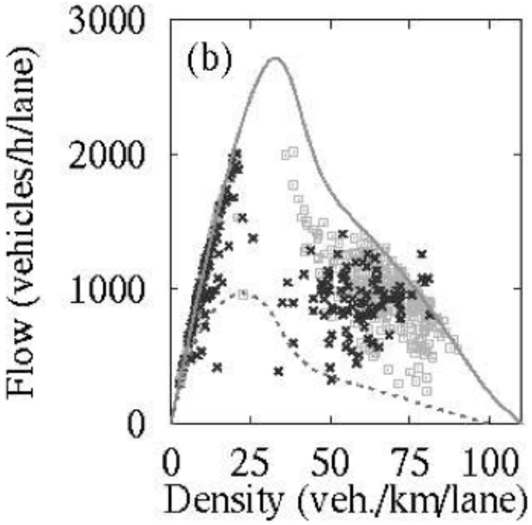


Figure 4. – Traffic Phase Diagram (D. Helbing. 2002 [17])

In Figure 4, the black x's are experimental data, the grey boxes are simulation data, and the lines are theoretical upper and lower bounds illustrating the bounds of maximum flow and congested flow.

These phase analysis techniques have yet to be applied to the three-dimensional motion of aircraft, but there is no fundamental reason why this cannot be done. Formulating a traffic physics paradigm for aircraft is important in that it allows one to formulate a general answer to a ubiquitous and important question: "When is the airspace 'full'?" without having to specify the details of a particular air traffic scenario. Furthermore, it can be used as a guide to engineering different local rules such as: "Can the airspace capacity be increased by a different choice of "particle interaction rules" (*i.e.,* aircraft navigation protocols)? Characterizing a system by its phase is different from using measures that are associated with individual agents or with small departures from equilibrium, such as Lyapunov exponents (20). Framing the system as a collection of agents lays the groundwork for characterizing the system's overall behavior or state.

Optimization and Logical Phase Transitions

A key part of creating a safe, robust, flexible, and efficient air traffic system is defining metrics that are measurable and can be optimized. Certain aspects of trajectory optimization are already well understood and implemented in some cases (21). Phase transitions were discussed in the context of physical systems of particles and traffic in the section above, but phase transitions also exist in *logical* systems such as schedules or other optimization problems. In a general optimization problem, the number of possible solutions will decrease (unless it is already zero) as the number of constraints increases. This decrease is often not gradual but rather sudden, and it looks like a typical physical phase transition such as that between water and ice with a sharp and well-defiined boundary.

Almost all optimization problems can be reduced to a construct known as SAT, short for "satisfiability" (22).)

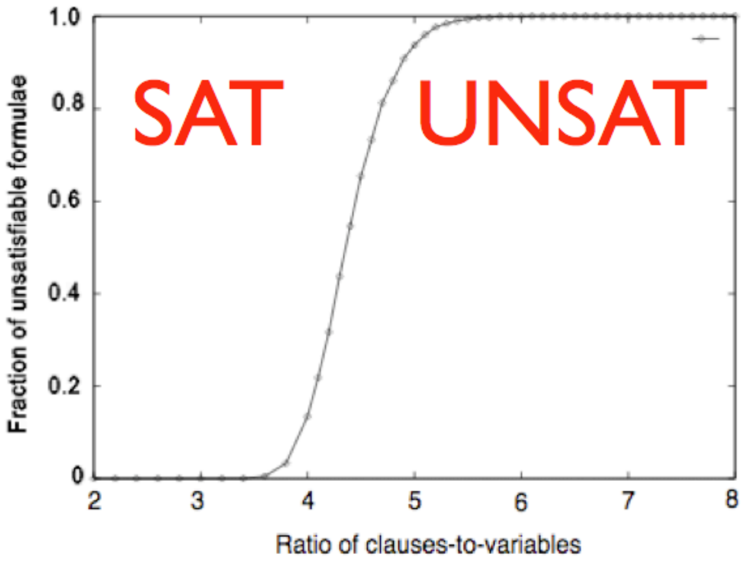


Figure 5. – Satisfiability Phase Transition (Kirkpatrick and Selman, 1994 [23])

The critical parameter for this phase transition is not temperature or pressure or vehicle density, but rather the density of constraints—the x-axis in Figure 5.

The logical and physical definitions for systems are intuitively connected if one takes the agent's point of view: If the molecule (or car or aircraft) has, on average, no options as to where to go next; then the system freezes up, or the traffic jams, or the system is "full." The mathematical connection between logical and physical phase transitions was established by Kirkpatrick and Selman (23) and others in the last ten years. This connection between the theory of optimization and the phase transition between viable and non-viable solution regions can provide insight into the definition of metrics for robustness and flexibility, both of which are related to the presence and "on the fly" accessibility of alternate solutions for an aircraft's trajectory.

Robustness can be interpreted as the presence of many solutions to a problem, and flexibility could be interpreted as the ease with which one can transition between these solutions (15). The solution of general SAT systems provides compelling insight (24) into these abstract concepts.

Managing Systemic Behavior

- Near phase transition
- Competing constraints
- Advance warning

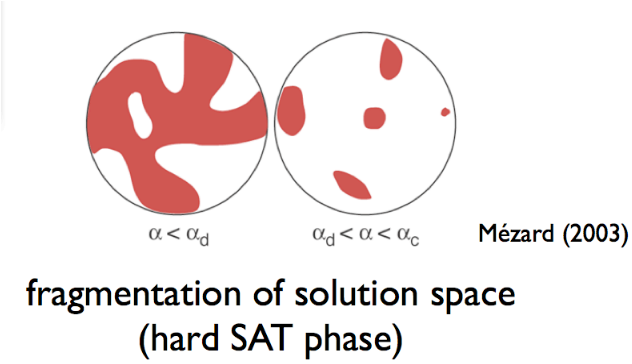


Figure 6. – Solution Space of SAT Problems – Near Phase Transition

In Figure 6, the solution space transforms from connected (on the left) to disconnected (right) as the phase transition boundary is approached, meaning that flexibility disappears before robustness does. This near-phase-transition phenomenon is also appealing because it means that there is an advance warning of the onset of a phase transition, something extremely useful in systems where humans might intervene to avoid undesirable dynamics. This phenomenon hints at the possibility of an emerging role for NextGen air traffic management systems: Managing systemic behavior rather than micromanaging individual aircraft behavior.

Conclusions

The outcome of a systems thinking approach to airspace management provides a novel and powerful approach to such challenging issues as:

1. How can airspace capacity be increased?
2. How can solutions among competing constraints be optimized?
3. When is the airspace full? How do we know it's close to full?
4. What aircraft interaction protocols generate safe and efficient flight as well a level business playing field for multiple players?
5. How can the workload (and costs) for air traffic management be reduced?
6. How can the behavior of aircraft be managed systemically rather than individually?

A systems thinking approach leads to the following prospects:

- If agent-based properties were imbued into trajectory mathematics, then the robustness, flexibility, and capacity of the airspace management system could be not only be measured but managed and enhanced with reduced workload and perhaps costs.
- If the agent-based trajectory properties accounted for aircraft operator business considerations, then the resulting trajectories could be managed for economic outcomes as well as for capacity and safety.
- If a facility such as the NASA ATOL were enhanced with a Flight Operations Service dispatch functionality, then the automated operation of a system for airspace management could be simulated to measure human-in-the-loop performance.

About the Authors:

Drs. Sawhill, Herriot, and Holmes are among the founders of NextGen AeroSciences, LLC. The company derives its technical foundation from their contributions in basic and applied research in the complexity and network sciences, computationally efficient combinatorial mathematics, and in air transportation system innovation (including developments at the Santa Fe Institute and NASA). The advancements of the 1990s led to Complex Adaptive Systems studies, agent-based models, and high-efficiency combinatorial mathematics, with widespread applications in communications, computing, economics, biology, chemistry, policy, social systems, and other fields including transportation. Their contributions led to innovations in automated, real-time logistics management systems for the first per-seat, on-demand air carrier (DayJet Corporation). The application of these tools to the DayJet per-seat, on-demand air carrier between 2001 and 2008 resulted in the first fully automated, integrated aircraft fleet management system for assigning passengers and pilots to aircraft, managing maintenance and training cycles, optimizing for disruptions, and providing full regulatory compliance in near real time. NextGen AeroSciences, LLC sees powerful opportunities to apply these tools to a variety of transportation system challenges, including dynamic flight trajectory optimization and management.

Cited References

1. NextGen defined. Feb. 5, 2009. Federal Aviation Administration. U.S. Department of Transportation. Mar. 5, 2009. <http://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=8145>.
2. Wiener N. 1948. Cybernetics: or the control and communication in the animal and the machine. Paris, France: Librairie Hermann & Cie, and Cambridge, MA: MIT Press.
3 Bertalanffy L von. 1976. General system theory: foundations, development, applications. Revised edition. New York: Braziller.
4. Foerster H von. 1974. Cybernetics of cybernetics. Urbana, Illinois: U of Illinois.
5. Weinberg G. 2001. An introduction to general systems thinking. New York: Dorset.
6. Holland JH. 1992. Adaptation in natural and artificial systems. Cambridge, MA: MIT Press.
7. Waldrop MM. 1993. Complexity: the emerging science at the edge of order and chaos. New York: Simon.
8. Kauffman SA. 1993. The origins of order: self-organization and selection in evolution. New York: Oxford UP.
9. Reynolds C. Sept. 6, 2001. Boids. (Flocks, herds, and schools: a distributed behavioral model). Mar. 3, 2009. <http://www.siggraph.org/education/materials/HyperGraph/animation/art_life/video/3cr.mov>.
10. Holmes BJ, Scott JM. April, 2004. Transportation network topologies. Paper presented at the 4th Integrated Communications, Navigation, and Surveillance (ICNS) Conference. Fairfax, Virginia.
11. ARPANET. Mar. 3, 2009. Wikipedia, The Free Encyclopedia. Mar. 4, 2009. <http://en.wikipedia.org/wiki/ARPANET>.
12. Neumann, J von, Morgenstern O. 1947. Theory of games and economic behavior. 2nd ed. Princeton: Princeton UP.
13. Nisan N, Ronen A. 2001. Algorithmic mechanism design. Games and Economic Behavior 35:166-96.
14. Varian HR. July 11 – 12, 1995. Economic mechanism design for computerized agents. In Proceedings of the 1st Conference on USENIX Workshop on Electronic Commerce – Vol. 1. New York, NY. 2.
15. Wolpert DH. 2003. Collective intelligence. Chapter 17. Computational Intelligence: The Experts Speak. Eds. David. B. Fogel and Charles. J. Robinson. USA: Wiley-IEEE.
16. Husni I, Vivon R, El-Wakil T. Feb. 2009. Distributed trajectory flexibility preservation for traffic complexity mitigation. Final briefing. NASA Research Announcement. L3 Communications.

17. Helbing D, and others. 2002. Micro-and macro-simulation of freeway traffic. Mathematical and Computer Modeling 35:517-47.

18. Budiansky S. Dec. 2000. The physics of gridlock. The Atlantic Online Feb. 28, 2009. <http://www.theatlantic.com/issues/2000/12/budiansky.htm >.

19. Helbing D. 2001. Traffic and related self-driven many-particle systems. Reviews of Modern Physics 73:1067-1141.

20. Lyapunov AM. 1994. The general problem of the stability of motion. Applied Mechanics 61(1):226.

21. Tocher JL, Curry RE. April 10, 1996. Benefits of optimal flight plans. In Proceedings of SPIE. Vol. 2737. Air Traffic Control Technologies II. Orlando, FL. 22.

22. Papadimitriou CH. 1994. Computational complexity. No p: Addison.

23. Kirkpatrick S, Selman B. 1994. Critical behavior in the satisfiability of random Boolean expressions. Science 264 (5163):1297-1301.

24. Mézard M, Palassini M, Rivoire O. 2005. Landscape of solutions in constraint satisfaction problems. Physical Review 95:200-02.

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