SWARM INTELLIGENCE

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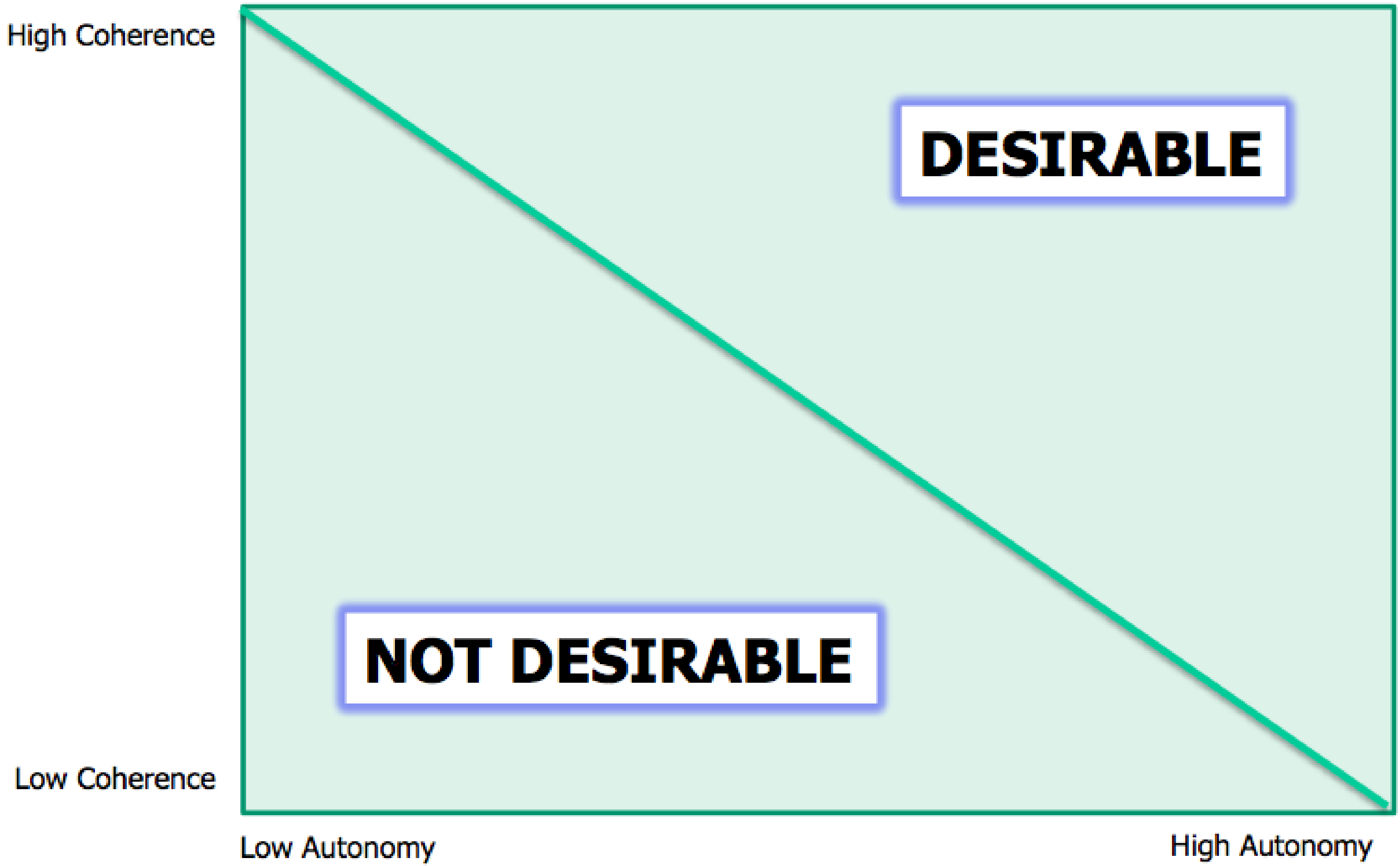
Local Decisions vs. Emergent Behavior 1

- Multiagent Systems: multiple agents acting in an environment to achieve goals

- Desirable property: **autonomy** -- agents make own decisions on how to act
  - More independence from other agents
  - Faster reaction to dynamic environment
  - Improved scalability and fault tolerance
  - Localized behavior to agent’s environment

- Challenge: how to balance coherent, desired emergent behavior (system-level) with autonomy (agent-level)

Local Decisions vs. Emergent Behavior 2



Local Decisions vs. Emergent Behavior 3

- Option 1: Reduce autonomy for coherence
  - Global directives to coordinate team
  - Common to human teams and organizations
    - Business organizations (Board of Directors, Management, Workers)
    - Military (Commander in Chief, Generals, Commanding Officers, Field Soldiers)
- Option 2: Highly capable agents
  - Agents optimize some local problem, leading to global solution (with possibly some local coordination)
  - What most people think of when they hear “agent”
    - Search and rescue robots
- Option 3: Swarms of very simple agents
  - Many, many agents performing very simple actions
  - Less optimization and intelligence, more self-organization
    - Viruses and human immune system

Introduction 1

- Swarm intelligence was originally used in the context of cellular robotic systems to describe the self-organization of simple mechanical agents through nearest-neighbor interaction

- It was later extended to include "any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies"

- This includes the behaviors of certain ants, honeybees, wasps, cockroaches, beetles, caterpillars, and termites

Introduction 2

- Many aspects of the collective activities of social insects, such as ants, are self-organizing
  - Complex group behavior emerges from the interactions of individuals who exhibit simple behaviors by themselves: finding food and building a nest
  - Self-organization come about from interactions based entirely on local information

IMPORTANT

Introduction 3

- Self-organization relies on several components
  - Positive feedback: the recruitment of other insects to forage a food source
  - Negative feedback: limitations on behavior caused by events such as the depletion of a food source
  - Amplification of fluctuations: necessity of random events, such as an ant getting lost but finding a new source of food to exploit
  - Multiple interactions: can be direct (visual, physical, or chemical) or indirect (stigmergy)

The Ant System 1

- Work by Dorigo, Minezzo and Colorni (1996)
- A general-purpose heuristic algorithm which can be used to solve different combinatorial optimization problems
  - Versatile
  - Robust
  - A population-based approach
- The Ant System

The Ant System 2

- One of the problems studied by enthologists was to understand how almost blind animals like ants could manage to establish shortest route paths from their colony to feeding sources and back

- It was found that the medium used to communication information among individuals regarding paths, and used to decide where to go, consists of pheromone trails

- A moving ant lays some pheromone (in varying quantities) on the ground, thus marking the path by a trail of this substance

The Ant System 3

- While an isolated ant moves essentially at random, an ant encountering previously laid trail can detect it and decide with high probability to follow it, thus reinforcing the trail with its own pheromone

- The collective behavior that emerges is a form of autocatalytic behavior (positive feedback) where the more the ants following a trail, the more attractive that trail becomes for being followed

RELIABLE SCOUT?

  - A higher level of pheromone gives an ant a stronger stimulus and thus a higher probability to choose a certain path

  - An ant chooses the path with the highest pheromone level to use on the return trip, further reinforcing the trail

The Ant System 4

- Videos of pheromone trails:
  - http://www.youtube.com/watch?v=tAe3PQdSqzg
  - http://www.youtube.com/watch?v=6WCQ1Q6Xoek
- Complex behaviors arising from simple ant actions:
  - http://www.youtube.com/watch?v=lFg21x2sj-M
  - http://www.youtube.com/watch?v=A042J0IDQK4
- Also seen elsewhere in nature:
  - http://www.youtube.com/watch?v=cIgHEhziUxU

The Ant System 5

- The Ant System and ant algorithms, derived from the study of real ant colonies

- Some major differences
  - Artificial ants will have some memory
  - They will not be completely blind
  - They will live in an environment where time is discrete

The Ant System 6

- There are *n* towns; each town has *b* ants
- Each ant is a simple agent with the following characteristics:
  - It chooses the town to go to with a probability that is a function of the town distance and of the amount of trail present on the connecting edge
  - To force the agent to make legal tours, transitions to already visited towns are disallowed until a tour is completed (this is controlled by a taboo list)
  - When it completes a tour, it lays a substance called trail on each edge visited

WHEN?

The Ant System 7

- The intensity of trail on edge (i,j) at time t is updated based on the evaporation rate of the trail between the time t and t-1, and the quantity of trail substance laid on the edge between t and t-1

- The longer the distance of an edge, the less visible the edge is

- The transition probability from one town to another is then the weighted product of visibility and trail intensity over the sum of all such products
  - Tradeoff between visibility and trail intensity

The Ant System 8

- The ant-cycle algorithm:
  - At time zero, an initialization phase takes place during which ants are positioned on different towns and initial values for trail intensity are set on edges
  - Thereafter, every ant moves from town to town, choosing the town to move to with a probability (a function of trail intensity and visibility)
  - After n iterations, all ants have completed a tour. For each ant, the value of the distance traversed is recoded. And the shortest path is also computed
  - This process iterates until the tour counter reaches a maximum or until all ants make the same tour (stagnation behavior)

The Ant System 9

- Video demonstration:
  - http://www.youtube.com/watch?v=SMc6UR5blS0

Behavior and Applications

- Insect behavior and applications
  - Looking for food: planning, space planning, constraint satisfaction
  - Arrangement of eggs: data management, sorting, grouping of database information
  - Transportation of food or retrieval of prey: robotics, assembly line design and balancing
  - Prefeeding trails: exploratory
  - Postfeeding trails: recruitment to lead others to the food sources
  - Role allocation: foragers, patrollers, nest maintainers, midden (refuse) workers
  - Older bees may forage for food, while younger bees will stay at the hive and nurse young: task allocation may change when demand dictates, flexible manufacturing process

Applications 1

- Symmetric and Asymmetric Traveling Salesman Problem (TSP)
  - Dorigo M., V. Maniezzo & A. Colorni (1996). The Ant System: Optimization by a Colony of Cooperating Agents. *IEEE Transactions on Systems, Man, and Cybernetics-Part B*, **26**(1):29-41
  - Colorni A., M.Dorigo, F.Maffioli, V. Maniezzo, G. Righini, M. Trubian (1996). Heuristics from Nature for Hard Combinatorial Problems. *International Transactions in Operational Research*, **3**(1):1-21.
  - Dorigo M. & L.M. Gambardella (1997). Ant Colony System: A Cooperative Learning Approach to the Traveling Salesman Problem. *IEEE Transactions on Evolutionary Computation*, **1**(1):53-66.

Applications 2

- The Sequential Ordering Problem
  - Gambardella L. M. and M. Dorigo (1997). HAS-SOP: An Hybrid Ant System for the Sequential Ordering Problem. Tech. Rep. No. IDSIA 97-11, IDSIA, Lugano, Switzerland.
- The Quadratic Assignment Problem
  - Gambardella L. M., E. Taillard and M. Dorigo (1999). Ant Colonies for the Quadratic Assignment Problem. *Journal of the Operational Research Society*, **50**:167-176.
  - Maniezzo V. and A. Colorni (1999). The Ant System Applied to the Quadratic Assignment Problem. *IEEE Transactions on Knowledge and Data Engineering*.

Applications 3

- The Vehicle Routing Problem
  - Bullnheimer B., R.F. Hartl and C. Strauss (1999). An Improved Ant system Algorithm for the Vehicle Routing Problem. *Annals of Operations Research* (Dawid, Feichtinger and Hartl (eds.): *Nonlinear Economic Dynamics and Control*, 1999.
  - Bullnheimer B., R.F. Hartl and C. Strauss (1999). Applying the Ant System to the Vehicle Routing Problem. In: Voss S., Martello S., Osman I.H., Roucairol C. (eds.), *Meta-Heuristics: Advances and Trends in Local Search Paradigms for Optimization*, Kluwer:Boston.

Applications 4

- Scheduling Problems
  - Colorni A., M. Dorigo, V. Maniezzo and M. Trubian (1994). Ant system for Job-shop Scheduling. *JORBEL - Belgian Journal of Operations Research, Statistics and Computer Science*, **34**(1):39-53.
- The Graph Coloring Problem
  - Costa D. and A. Hertz (1997). Ants Can Colour Graphs. *Journal of the Operational Research Society*, **48**, 295-305.

Applications 5

- Partitioning Problems
  - Kuntz P. and D. Snyers (1994). Emergent Colonization and Graph Partitioning. Proceedings of the Third International Conference on Simulation of Adaptive Behavior: From Animals to Animats 3, MIT Press, Cambridge, MA.
  - Kuntz P., P. Layzell and D. Snyers (1997). A Colony of Ant-like Agents for Partitioning in VLSI Technology. Proceedings of the Fourth European Conference on Artificial Life, P. Husbands and I. Harvey, (Eds.), 417-424, MIT Press.

Applications 6

- Telecommunications Networks
  - Schoonderwoerd R., O. Holland, J. Bruten and L. Rothkrantz (1997). Ant-based Load Balancing in Telecommunications Networks. *Adaptive Behavior*, **5**(2):169-207.
  - Di Caro G. and M. Dorigo (1998). Mobile Agents for Adaptive Routing. *Proc. of 31st Hawaii Int. Conf. on System*, 74-83.
  - Di Caro G. & Dorigo M. (1998). AntNet: Distributed Stigmergetic Control for Communications Networks. *J. Artificial Intelligence Research (JAIR)*, **9**:317-365.
  - Navarro Varela G. and M.C. Sinclair (1999). Ant Colony Optimisation for Virtual-Wavelength-Path Routing and Wavelength Allocation. *Proc. of the Congress on Evolutionary Computation (CEC'99)*, Washington DC, USA, July 1999.

Applications 7

- Parallel Implementations
  - Bullnheimer B., G. Kotsis, C. Strauss (1998). Parallelization Strategies for the Ant System. In: R. De Leone, A. Murli, P. Pardalos, G. Toraldo (eds.), *High Performance Algorithms and Software in Nonlinear Optimization; series: Applied Optimization*, Vol. **24**, Kluwer:Dordrecht, 87-100.
- The Single Machine Total Tardiness Problem
  - Bauer, A., B. Bullnheimer, R. F. Hartl, and C. Strauss (1999). An Ant Colony Optimization Approach for the Single Machine Tardiness Problem. *Proc. of 1999 Congress on Evolutionary Computation*, 1445-1450.

Applications 8

- The Power Economic Dispatch Problem
  - Song, Y. H., C. S. V. Chou, and Y. Min (1998). Large-Scale Economic Dispatch by Artificial Ant Colony Search Algorithms, *Electric Machines and Power Systems*, **27**(7):87-100.
- Others
  - Leerink L.R., S.R. Schultz and M.A. Jabri (1995). A Reinforcement Learning Exploration Strategy based on Ant Foraging Mechanisms. *Proc. of 6th Australian Conf. on Neural Networks*, Sydney, Australia, 1995

More Recent … 1 (based on Google search)

- **Ant-based and swarm-based clustering** J Handl… - **Swarm** Intelligence, 2007 - Springer
  ... Given that the focus of our paper is on **ant-based** and **swarm**-based clustering, we will discuss the use of ant colony optimization (ACO) (Dorigo and **...** In ACO a number of agents ("ants") independently construct **solutions** in parallel by iteratively augmenting partial so- lutions. **...**
  Cited by 59 - Related articles - Print @ UNL - BL Direct - All 3 versions
- **[HTML] Swarm intelligence** M. Dorigo, M Birattari - Scholarpedia, 2007 - scholarpedia.org
  ... in the search space where the neighbor particles found the best **solution** so far. **...** The first **swarm**-based approaches to network management were proposed in 1996 by Schoonderwoerd et al **...** proposed **Ant-based** Control (ABC), an algorithm for routing and load balancing in circuit **...**
  Cited by 66 - Related articles - Cached - Print @ UNL - All 5 versions
- **The intelligent water drops algorithm: a nature-inspired swarm-based optimization algorithm** H Shah-Hosseini - International Journal of Bio-Inspired Computation, 2009 - Inderscience
  ... Moreover, the IWDs may gain different velocities throughout an iteration of the IWD algorithm whereas in **ant-based** algorithms the velocities of the **...** A **swarm** of IWDs flows in the graph with the guidance of a local heuristic in the hope of finding optimal or near optimal **solutions**. **...**
  Cited by 20 - Related articles - Print @ UNL - All 6 versions
- **Ant colony optimization for continuous domains** K. Socha… - European Journal of Operational Research, 2008 – Elsevier **...** View the MathML source and other **swarm**-based algorithms 4.2. **...** Usually these problems are tackled with heuristic methods (ie, not exact methods) that permit to find approximate **solutions** (ie, **solutions** that are good, but not provably optimal) in a reasonable amount of time. **...**
  Cited by 244 - Related articles - All 17 versions
- **Estimation-based ant colony optimization and local search for the probabilistic traveling salesman problem** PBalaprakash, M Birattari, T Stützle, Z Yuan… - **Swarm** Intelligence, 2009 - Springer
  ... Student's t-test, which is appropriate for comparing two **solutions**. However, since in ACS more than two **solutions** are compared at Page 9. **Swarm** Intell (2009) 3: 223–242 231 each iteration, we use a parametric statistical test based **...**
  Cited by 7 - Related articles - Print @ UNL - All 14 versions

More Recent … 2 (based on Google search)

- **Using swarming agents for scalable security in large network environments** MB Crouse, JL White, EW Fulp… - …), 2011 IEEE 54th …, 2011 - ieeexplore.ieee.org
  ... do not depend on particular individual agents [5]. These features of **swarm solutions** are important **...**
  A **SWARM**-BASED ApPROACH TO SECURITY The digital ants framework is a hierarchy consisting **...**
  G. A, Fink, WM Maiden, D, McKinnon, and EW Fulp, "**Ant-based** cyber defense **...**
  Print @ UNL
- **Dynamic routing exponent strategies for ant-based protocols** R Fang, Z Huang, L Rossi… - Applications of Evolutionary …, 2011 - Springer
  ... route **solutions** correspond to paths that have the smallest hop count. In this paper, we leverage this idea to improve the performance of **ant-based** routing protocols by dynamically adjusting the routing exponent. The results are validated via simulation. 1 Introduction **Swarm ...**
  Related articles - Print @ UNL - All 2 versions
- **Swarm intelligence systems for transportation engineering: Principles and applications** D Teodorovic - Transportation Research Part C: Emerging …, 2008 - Elsevier
  ... The term "**Swarm** intelligence", denoting this "collective intelligence" has come into use ([Beni, 1988], [Beni and Wang, 1989], [Beni and Hackwood, 1992] and [Bonabeau et al **...** As we can see, artificial ants collaborate among themselves in order to discover high-quality **solutions**. **...**
  Cited by 36 - Related articles - All 4 versions
- **Modeling, analysis and simulation of ant-based network routing protocols** CE Torres, LF Rossi, J Keffer, K Li… - **Swarm** Intelligence, 2010 - Springer
  ... Abstract Using the metaphor of **swarm** intelligence, **ant-based** routing protocols deploy control packets that behave like ants to discover and optimize routes between pairs of nodes. These **ant-based** routing protocols provide an elegant, scalable **solution** to the routing problem **...**
  Cited by 2 - Related articles - Print @ UNL - All 3 versions
- **Particle swarm optimization in wireless-sensor networks: A brief survey** RV Kulkarni… - Systems, Man, and …, 2011 - ieeexplore.ieee.org
  ... In **ant-based** optimization, artificial ants move from a node to another constructing a partial **solution** to the **...** Once an ant reaches the final node, the performance of the **solution** is evalu ated and the **...**
  Swarm agents are used to evolve the choice of sensors (each agent is a subset of **...**
  Cited by 7 - Related articles - All 4 versions

More Recent … 3 (based on Google search)

- **Editorial survey: swarm intelligence for data mining** D Martens, B Baesens… - Machine learning, 2011 - Springer
  ... mapping **solution** of the data. In this category of clustering techniques fall **ant-based** sorting and
  prey models. A high-level algorithmic description of these approaches is described in Algorithms
  1 and 2. Both approaches start by defining the environment in which the **swarm ...**
  Cited by 8 - Related articles - All 16 versions
- **Thermal Unit Commitment using improved ant colony optimization algorithm via Lagrange multipliers** FR Nascimento, IC Silva, EJ Oliveira… - PowerTech, 2011 …, 2011 - ieeexplore.ieee.org
  ... through the use of the primal-dual interior-point method, generating Lagrange multipliers
  associated to the ON/OFF decision variables as subproducts which are used to draw up a list
  of priorities, where part of the colony will make use of this information in the search for **solutions ...**
  Related articles - Print @ UNL
- **Ant colony optimization** M Dorigo, M Birattari… - … Intelligence Magazine, IEEE, 2006 - ieeexplore.ieee.org
  ... Swarm intelligence is a relative- ly new approach to problem solving that takes inspiration from
  the social behaviors of insects and of other animals. **...** In ACO, a number of artificial ants build
  solutions to the considered optimization problem at hand and exchange **...**
  Cited by 546 - Related articles - Library Search - All 31 versions
- **A review of the application of swarm intelligence algorithms to 2D cutting and packing problem** Y Xu, G Yang, J Bai… - Advances in **Swarm** Intelligence, 2011 - Springer
  ... 67 3 Applications of **Swarm** Intelligence Algorithms in 2D Cutting and Packing Problem **...** This
  approach may get steady performance and a good **solution** even not finding the optimum. **...** They
  use an **ant-based** algorithm and optimize the packing order with the base of this heuristic. **...**
  Related articles - Print @ UNL - All 2 versions
- **A review of ant algorithms** RJ Mullen, D Monekosso, S Barman… - Expert Systems with …, 2009 - Elsevier
  ... With this, approximation algorithms have received much attention, in order to compute accurate
  solutions in significantly less time. **...** Within the Artificial Intelligence (AI) community, ant algorithms
  are considered under the category of **swarm** intelligence (Bonabeau, Dorigo, & **...**
  Cited by 42 - Related articles - All 8 versions

Swarm 1

- Work by Santa Fe Institute (1994-present)
- The primary goal of the Swarm simulation system is to save researchers from having to deal with all of the programming issues involved in the implementation of concurrent, distributed artificial worlds
- Swarm provides a wide spectrum of generic artificial worlds populated with generic agents, a large library of design and analysis tools, and a kernel to drive the simulation

Swarm 2

- Swarm 1994
  - Written in pure C
  - Object-oriented in style: Everything in Swarm is an object
  - Objects communicate with other objects by sending them messages
  - All inhabitants of the artificial world (bugs, economic agents, molecules) are objects

IMPORTANT

  - Visualization tools part of software

Swarm 3

- Swarm 1995
  - For physics, biology, economics, anthropology
  - Object-oriented libraries include Agents, Analysis, I/O, Utilities, Worlds, Design Tools, Visualization, and Spaces
  - Discrete-event, time-stepped schedules
  - Hierarchical organization of agents, and of schedules
  - Parallelism and concurrency: different swarms can be run on different processors
  - Some learning mechanism through reflective roles of nested swarms

IMPORTANT

Swarm 4

- Swarm 1996
  - Multiagent discrete event simulation
  - Heterogeneous swarms
    - Different animal groups within a swarm
    - Multi-level modeling
  - Object-oriented for direct instantiation and subclassing
  - Simulation libraries, Swarm support libraries, Model-specific libraries

Swarm 5

- Fast forward:

Contents

Swarm 6

- FAQ (the largest FAQ maintained for Swarm …)

http://pj.freefaculty.org/SwarmFaq/SwarmOnlineFaq.html

Websites & References

- iridia.ulb.ac.be/~mdorigo/ACO/ACO.html – Original Ant Colony Optimization website
- www.swarm.org – The Swarm Development Group

- Tarasewich, P. and P. R. McMullen (2002). Swarm Intelligence: Power in Numbers, *Communications of the ACM*, **45**(8):62-67.
- Dorigo, M., V. Maniezzo, and A. Colorni (1996). The Ant System: Optimization by a Colony of Cooperating Agents, *IEEE Transactions on Systems, Man, and Cybernetics-Part B*, **26**(1):1-13.