

SWARM INTELLIGENCE

Leen-Kiat Soh

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Department of Computer Science and Engineering

University of Nebraska

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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

- 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: Pheromone

- One of the problems studied by entomologists 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: Emergent Behavior

- 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
 - 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

RELIABLE SCOUT?

The Ant System: The Algorithm

- 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: A Real-World Problem

- 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 tabu list)
 - When it completes a tour, it lays a substance called **trail** on each edge visited

The Ant System: How It Works

- 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

The Ant System: The Algorithm's Ant-Cycle

- 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 recorded. 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**)

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. Coloni (1996). The Ant System: Optimization by a Colony of Cooperating Agents. *IEEE Transactions on Systems, Man, and Cybernetics-Part B*, **26**(1):29-41
 - Coloni 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 evaluated 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

- Work by Santa Fe Institute
- 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 Software

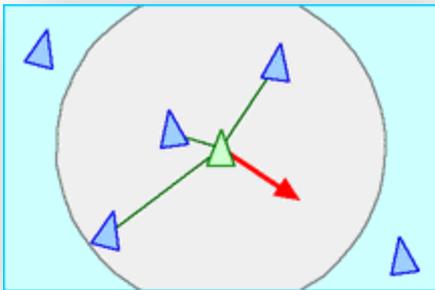
- Fast forward to today:

Contents

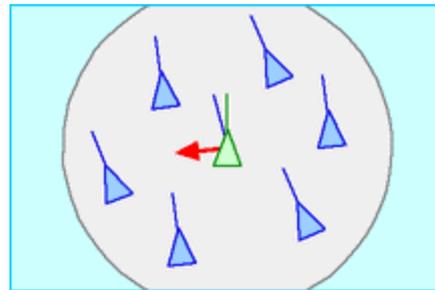
- 1 Stable release: Swarm 2.2
- 2 Notes
- 3 Packaged (binary) distributions (2.2)
 - 3.1 Windows binaries for Objective-C Swarm
 - 3.1.1 MinGW Windows binaries
 - 3.1.2 Cygwin Windows binaries
 - 3.2 Windows binaries for Java Swarm
 - 3.3 GNU/Linux binaries
 - 3.4 MacOS X binaries
 - 3.5 Other platforms
 - 3.6 Binaries of previous versions
- 4 Swarm source (2.2)
 - 4.1 Compiling Swarm for Windows from source using MinGW
 - 4.2 Compiling Swarm from source on Ubuntu and Debian Linux
- 5 Important Note For Linux/Unix Users on the gcc Compiler
- 6 Known bugs and fixes
 - 6.1 Error in Averager minimum, maximum values

Flocking

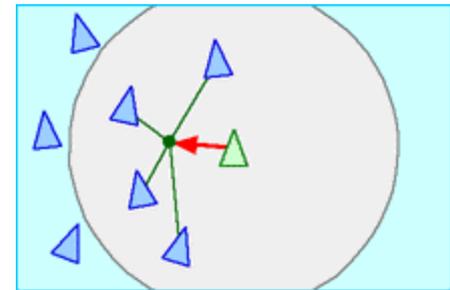
- Flocks, Herds, and Schools: A Distributed Behavioral Model, by Craig W. Reynolds Symbolics Graphics Division
- Boids
- the behaviors that lead to simulated flocking are:
 - **Collision Avoidance:** avoid collisions with nearby flockmates
 - **Velocity Matching:** attempt to match velocity with nearby flockmates (both speed and direction)
 - **Flock Centering:** attempt to stay close to nearby flockmates



separation



alignment



cohesion

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. Coloni (1996). The Ant System: Optimization by a Colony of Cooperating Agents, *IEEE Transactions on Systems, Man, and Cybernetics-Part B*, **26**(1):1-13.

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