CSCI 540 –Self Organizing Systems (3 units, Irregular)

Introduction and Course Description:

How come leopards have spots and zebras have stripes? How come some embryonic stem cells "know" that they should generate hands with five fingers? These are examples of self-organization, which is ubiquitous not only in biology but in other disciplines such as physics (think of crystals) or chemistry. Self-organizing systems are highly distributed; they are composed of large numbers of agents that execute tasks with no direct control or guidance from the exterior.

The course looks at biology for inspiration, but seeks to study engineered systems that exhibit self-organizing behavior. Ultimately we would like to be able to design such systems as well as "understand" how biosystems work. Because self-organization is a very broad topic, we focus on systems composed of "active" agents that have characteristics similar to those of robots or of biological cells rather than of "passive" molecules. Furthermore, we are primarily interested in spatial tasks such as constructing specific shapes. A major goal is to build "programmable matter", that is, devise systems that are capable of assembling themselves into desired (i.e., programmed) shapes from unstructured swarms of simple agents.

Self-organizing systems exhibit complex global behaviors that emerge from the simple local interactions between their constituent agents. These systems are robust to faults, adapt to dynamically-changing environments, do not have a "boss" to tell agents what to do, and are scalable, i.e., the number of their agents can become very large. These are very desirable properties, especially if the individual agents are very small (at the micro or nano scale) and therefore have limited capabilities and a significant probability of malfunctioning.

Interest in self-organizing systems is increasing rapidly. Thus, for example, NASA is studying robot swarms for space exploration, several groups are looking at potential biomedical applications, a large research program is in place in Europe, the entertainment industry is looking at swarms to create large numbers of virtual characters, several academic groups in the US and abroad are conducting research in the area, and the military are also interested since this is a new and powerful technology. Self-organization and related topics such as self-repair, self-assembly, swarm intelligence, and so forth, are quickly becoming mainstream, and this is a good time to learn about them. CS students may use the course to satisfy a PhD depth requirement in robotics or as a component of an MS in Intellligent Robotics.

Objectives: Students will acquire cutting-edge knowledge of a new an important research and development area, which has a firm basis on computer science. They will also develop skills required to read the current research literature and critically analyze it. The course can also be viewed as preparation for research on a crucial problem that is ubiquitous throughout the presentations: how can robot swarms and similar systems be "programmed" locally, at the agent level, so as to achieve global goals at the system level. This is sometimes called the “global-to-local compilation” or “inverse” problem, and is still largely open.

Catalog Description: Massively distributed systems whose global behavior emerges from the local interactions of their components. Global to local compilation. Robot swarms. Formation of shapes and spatial patterns. Self-assembly and programmable matter. Graduate standing in science or engineering.

Time: Tuesdays and Thursdays, 2:00 - 3:20 p.m.

Room: VHE214

Instructor: Prof. Aristides A. G. Requicha, SAL 202, requicha "At' usc.edu

Office Hours: Tuesdays and Thursdays, 3:30 - 5:00 pm.

TA: None.

Prerequisites: Graduate standing in any science or engineering discipline. Knowledge of robotics is useful, but not required. The course is relevant mostly to CS and EE students, especially those interested in robotics, but other computationally-inclined engineering or science students may find it interesting and useful.

Text: None. Readings from the research literature. References are listed below.

Approach: Lectures, and class discussions. Discussions will first make sure we all understand the material presented in class, and then look carefully at the limitations of the various systems, and what is good and bad about them. Reading the relevant literature ahead of time and building a personal list of questions and comments is recommended, so as to have meaningful and well-informed discussions in class.

Assignments: This course covers a fascinating topic and is meant to be fun and exciting. Students will have the opportunity to explore topics they find especially interesting. Grades will be based on the students' contributions to class discussions (see above), written critiques to assigned papers in the research literature, and on either a project or a term paper. Typical term papers will provide a critical literature review of subjects not covered in class but related to the course material, or propose research directions (which might lead to theses). Typical projects will involve implementing a simulator for one of the systems studied in class (or related to them), or using a publicly-available simulator and experimenting with it, for example, to study the system’s performance and limitations. All projects and term paper topics must be approved by the instructor on the basis of short proposals (1-2 pages) submitted by the students ***before*** embarking on the work. Proposals will be due about 1.5 months before the end of classes. Term papers and projects will be due a week before the end of classes. Collaborative projects are encouraged, especially with teams composed by students of different disciplines.

Thinking about projects before the proposal deadline is highly encouraged, and students are expected to demonstrate initiative in the selection of their term papers/projects.

Grading: Class participation/discussion 25%; Written critiques of assigned papers 25%; Project/term paper 50%.

Schedule and References:

Lecture 1: *Introduction*

Lectures 2, 3, 4: *Aggregation*

Sensor-guided aggregation
Gross et al. (2006) IEEE Trans. Robotics **22** (6):1115-1130

Diffusion-limited aggregation
L. M. Sander (2000) Contemporary Physics **41** (4):203-218

Control-theoretic approach
V. Gazi and K. M. Passino (2011) Swarm stability and optimization, Springer, Chapter 3.

Lectures 5, 6, 7: *Flocks and formations*

"Boid" flocks
C. W. Reynolds (1987) Computer Graphics **21** (4):25-34

Leader-follower systems
D. J. Naffin and G. S. Sukhatme (2004) Proc. 8^{th} Conf. on Intelligent Autonomous Systems 181-190

Control-theoretic formations
V. Gazi and K. M. Passino (2011) Swarm stability and optimization, Springer, Chapter 3.

Lectures 8, 9: *Spatial patterns in social insects*

Ant foraging and stigmergy
E. Bonabeau, M. Dorigo and G. Théraulaz (1999) Swarm Intelligence: From Natural to Artificial Systems, Oxford University Press, Section 2.2.

Ant wall building
Bonabeau et al., Sections 5.4 and 4.3
S. Camazine et al. (2001) Self-Organization in Biological Systems, Princeton University Press, Chapter 17

Wasp nest construction
Bonabeau et al., Chapter 6
Camazine et al., Chapter 19
G. Theraulaz and E. Bonabeau (1995) Science **269** : 686-688
G. Theraulaz and E. Bonabeau (1995) J. Theoretical Biology **177** (4):381-400

Lectures 10, 11, 12: *Random walks, diffusion theory and motion in a fluid*

1-D Random walk
H. C. Berg (1993) Random walks in biology, Princeton University Press, Chapter 1.

Fick's equations
Berg, Chapter 2

Diffusion with drift
Berg, Chapter 4.

Viscous flow
Berg, Chapter 4

Self-propelled objects at low Reynold numbers
Berg, Chapter 6

Lectures 13, 14: *Reaction-diffusion (Turing) systems*

Intuition
A. M. Turing (1952) "The chemical basis of morphogenesis" Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences **237**: 37-72.

S. Kondo and T. Miura (2010) Science **329** (5999):1616-1620.

Turing's example
Turing, above

Mathematical formulation
J. D. Murray (2003) Mathematical Biology, Volume II, Spatial Models and Biomedical Applications, Springer Verlag, Chapters 2 and 3.

Results and discussion
J. D. Murray (1988) "How the leopard gets its spots" Scientific American **259** (3): 80-87.

Lecture 15: *Cellular automata*

A. Deutsch and S. Dormann (2005) Cellular automaton modeling of biological pattern formation, Birkhäuser, Chapters 4 and 6.

G. W. Flake (1998) The computational beauty of nature, MIT Press, Chapter 15

Lectures 16, 17: *Graph grammars for assembly*

E. Klavins, R. Ghrist and D. Lipsky (2006) "A grammatical approach to self-organizing robotic systems" IEEE Trans. on Automatic Control **51** (6):949-962.

Lectures 18, 19: *Digital hormones*

W.-M. Shen et al. (2004) Autonomous Robots **17**:93-105

Lectures 20, 21: *Directional self-assembly*

A. L. Christensen et al. (2007) IEEE Robotics and Automation Magazine **14** (4):18-25.

A. L. Christensen et al. (2008) Swarm Intelligence 2:143-165

N. Matthews et al. (2011) IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS):4762-4769, San Francisco, CA, September 25-30

Lectures 22: *Adaptive-density formations*

J. Cheng et al. (2005) AAAI 05, July 2005

Lecture 23: *Robotic construction of block structures*

J. Werfel et al (2005) Int. J. Conf. on Artificial Intelligence :1495-1502

Lectures 24, 25: *The USC active self-assembly system*

D. J. Arbuckle and A. A. G. Requicha (2010) Autonomous Robots **28** (2):197-211

T. Tangchoopong and A. A. G. Requicha, "An empirical study of the performance of active self-assembly", *Proc. IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems* (*IROS '09*), St. Louis, MO, pp. 1838-1842, October 11-15, 2009.

Lectures 26, 27, 28: *An introduction to developmental biology*

L. Wolpert and C. Tickle, Principles of Development. Oxford University Press, 4^{th}. Edition, 2010, Chapter 1.

A. D. Lander, "Morpheus unbound: reimagining the morphogen gradient", *Cell* **128**:245-256, January 2007

Lectures 29, 30 Project and term paper presentations.

Statement for Students with Disabilities (required)

Any student requesting academic accommodations based on a disability is required to register with Disability Services and Programs (DSP) each semester. A letter of verification for approved accommodations can be obtained from DSP. Please be sure the letter is delivered to me (or to TA) as early in the semester as possible. DSP is located in STU 301 and is open 8:30 a.m.–5:00 p.m., Monday through Friday. The phone number for DSP is (213) 740-0776.

Statement on Academic Integrity (required)

USC seeks to maintain an optimal learning environment. General principles of academic honesty include the concept of respect for the intellectual property of others, the expectation that individual work will be submitted unless otherwise allowed by an instructor, and the obligations both to protect one's own academic work from misuse by others as well as to avoid using another's work as one's own. All students are expected to understand and abide by these principles. *Scampus,* the Student Guidebook, contains the Student Conduct Code in Section 11.00, while the recommended sanctions are located in Appendix A: http://www.usc.edu/dept/publications/SCAMPUS/gov/. Students will be referred to the Office of Student Judicial Affairs and Community Standards for further review, should there be any suspicion of academic dishonesty. The Review process can be found at: http://www.usc.edu/student-affairs/SJACS/.

Incompletes:

Not finishing the project on time is not an acceptable reason to get an incomplete. This is forbidden by the University, which specifically requires that incompletes be given only for serious health problems and similar reasons. For additional information, see: http://www.usc.edu/dept/ARR/private/forms/Handbooks/Grade_Handbook_rev082010.pdf .

Last Update: August 11, 2015