Swarm Intelligence and Extended Analog Computing

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The Roots of Swarm Intelligence

- Social psychology
  - Flocking, swarming, and schooling
  - Models of societies
  - Artificial life
- Evolutionary computation
  - A computational intelligence methodology
  - Concepts and algorithms roughly based on theories of evolution

Culture and Cognition Summary

- Individuals searching for solutions learn from the experiences of others (individuals learn from their neighbors)
- An observer of the population perceives phenomena of which the individuals are the parts (individuals that interact frequently become similar)
- Culture affects the performance of individuals that comprise it (individuals gain benefit by imitating their neighbors)

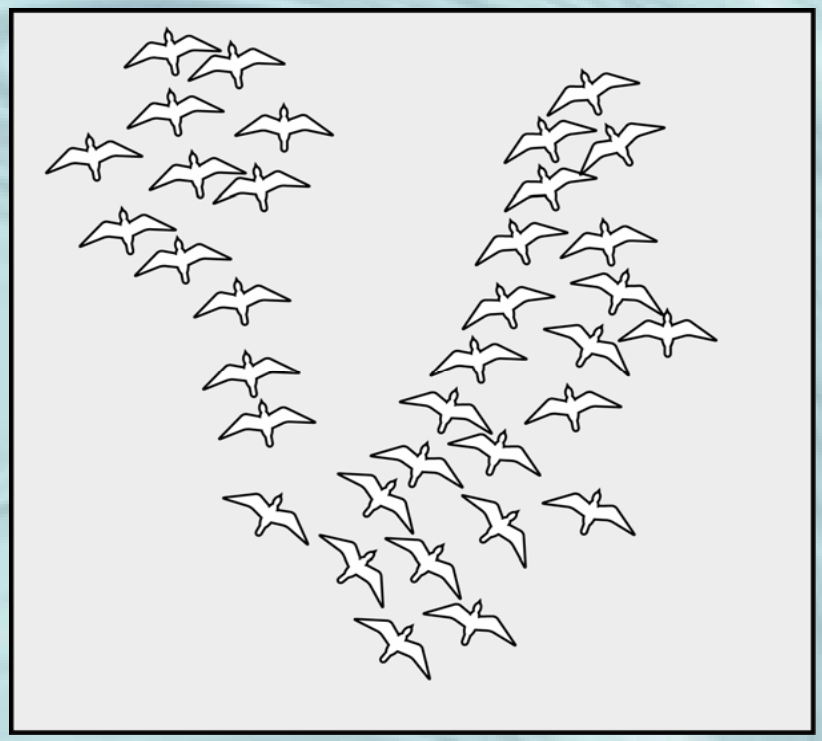
So, what about intelligence?

- Social behavior increases the ability of an individual to adapt
- There is a relationship between adaptability and intelligence
- Intelligence arises from interactions among individuals

Flocks, Herds, and Schools...

- Heppner & Grenander
- Craig Reynolds
- Toshio Fukuda
- Toner & Tu

- Steer toward the center
- Match neighbors' velocity
- Avoid collisions
- (Seek roost)

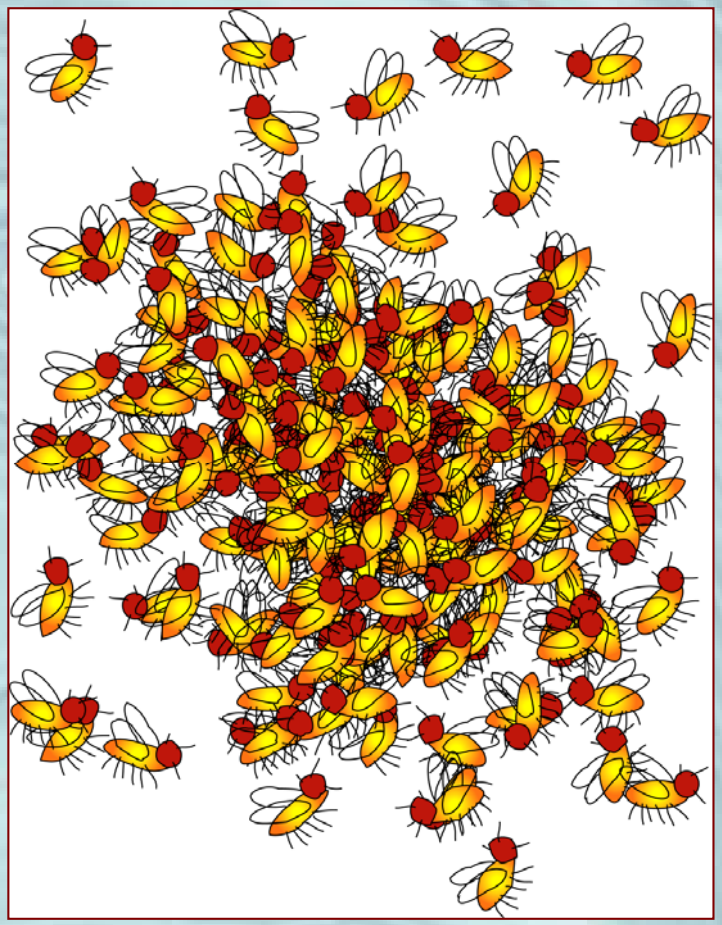


...And Swarms

Coherence without choreography

Bonabeau, Millonas, J.-L. Deneubourg, Langton, etc.

Particle swarms (physical position not a factor)



Swarm Intelligence: Definition

The adaptive behavior of a population of simple entities that interact either directly or indirectly. Swarm-intelligent systems often solve problems, converging or clustering in a problem space, and are usually stochastic. They often exhibit the property of self-organization.

Intelligent Swarm

- A population of interacting individuals that optimizes a function or goal by collectively adapting to the local and/or global environment
- Swarm intelligence ≅ collective adaptation

Adaptation is any process whereby a structure is progressively modified to give better performance in its environment. - *John Holland*

Swarm Intelligence Paradigm Examples

- Cultural algorithms
- Ant colony optimization
- Particle swarm optimization
- Others, and hybrids!

Particle Swarm Optimization

- A concept for optimizing complex nonlinear functions
- Has roots in artificial life and evolutionary computation
- Simple in concept
- Easy to implement
- Computationally efficient
- Effective on a wide variety of problems
- Seamlessly combines human knowledge and machine computational power
- IEEE Pioneer Award for Evolutionary Computation to Kennedy and Eberhart, 2012

Introduction to Particle Swarm Optimization

- A “swarm” is an apparently disorganized collection (population) of moving individuals that tend to cluster together while each individual seems to be moving in a random direction
- We also use “swarm” to describe a certain family of social processes

Features of Particle Swarm Optimization

- Population initialized by assigning random positions *and* velocities; potential solutions are then *flown* through hyperspace.
- Each particle keeps track of its "best" (highest fitness) position in hyperspace.
  - This is called "pbest" for an individual particle
  - It is called "gbest" for the best in the population
  - It is called "lbest" for the best in a defined neighborhood
- At each time step, each particle stochastically accelerates toward its pbest and gbest (or lbest).

Particle Swarm Optimization Process

1. Initialize population in hyperspace.
2. Evaluate fitness of individual particles.
3. Modify velocities based on previous best and global (or neighborhood) best.
4. Terminate on some condition.
5. Go to step 2.

PSO Velocity Update Equations

$$v_{id} = wv_{id} + c_1 rand()\left(p_{id} - x_{id}\right) + c_2 Rand()\left(p_{gd} - x_{id}\right)$$

$$x_{id} = x_{id} + v_{id}$$

Where ***d*** **is the dimension,** c_1 **and** c_2 **are positive constants,** ***rand*** **and** ***Rand*** **are random functions, and** ***w*** **is the inertia weight.**

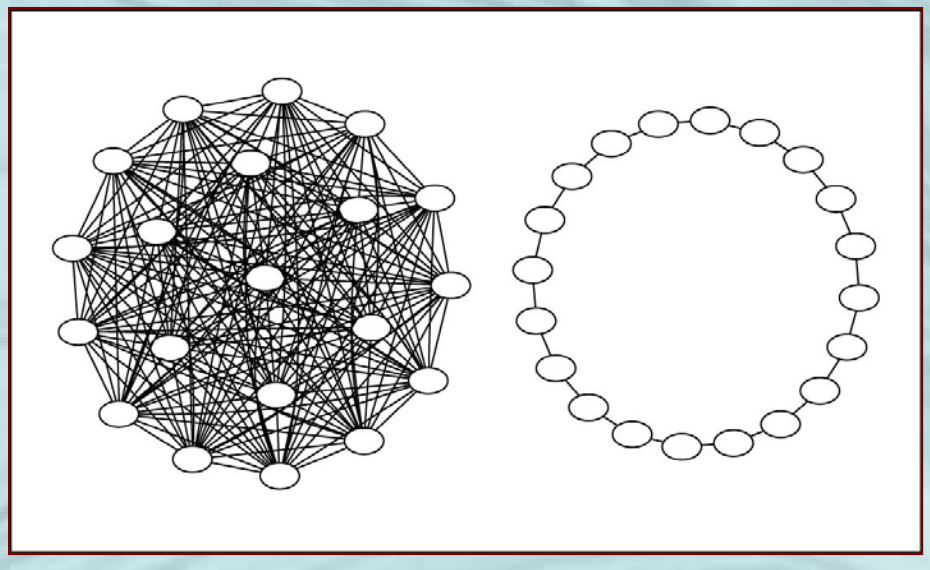
For the neighborhood version, change p_{gd} **to** p_{ld} **.**

VMAX

- An important parameter in PSO
- Clamps particles' velocities on each dimension
- Determines "fineness" with which regions are searched
  - If too high, can fly past optimal solutions
  - If too low, can get stuck in local minima

Population Topology

Patterns of connectedness between individuals = social network
Controls how solutions can flow through the population



Gbest and Lbest topologies

Extended Analog Computing

The developers of the EAC

Bryce Himebaugh, left, and Prof. Jonathan Mills, right,
Indiana University, Bloomington, Indiana.

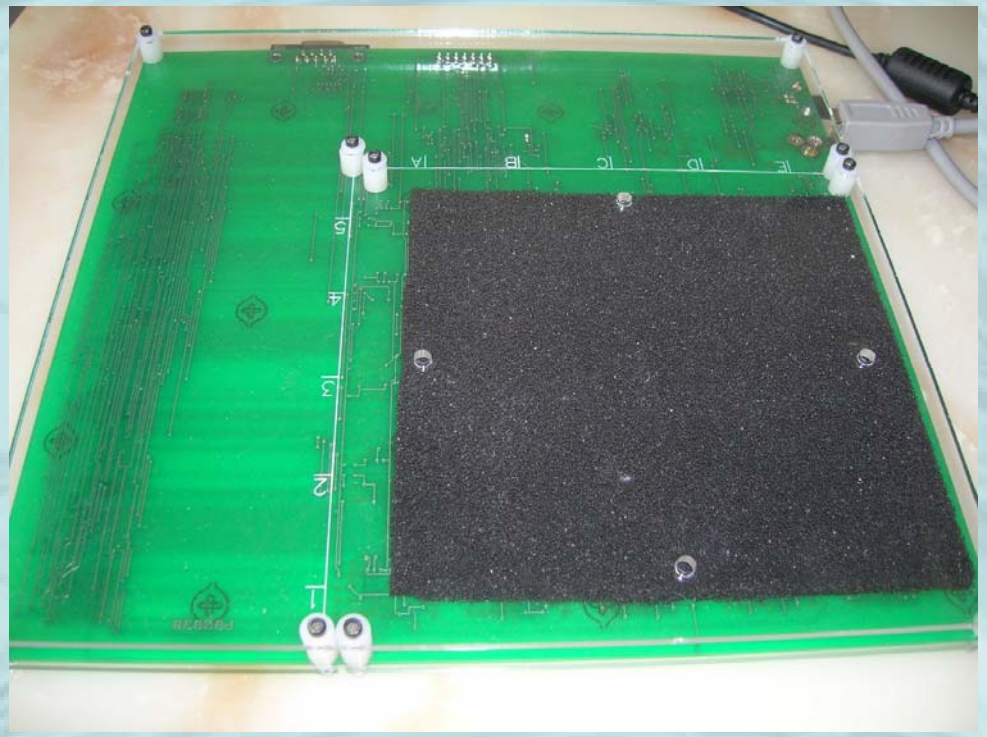
Extended Analog Computing

- An extended analog computer is a continuous-valued, implicitly parallel, reconfigurable processor
- It operates within a framework of a continuous distributed computational model that is implemented with structures that are configured (not programmed)
- Configuration can be accomplished using evolutionary algorithms such as particle swarm optimization
- Is a paradigm (example) of the concept of **natural computing**

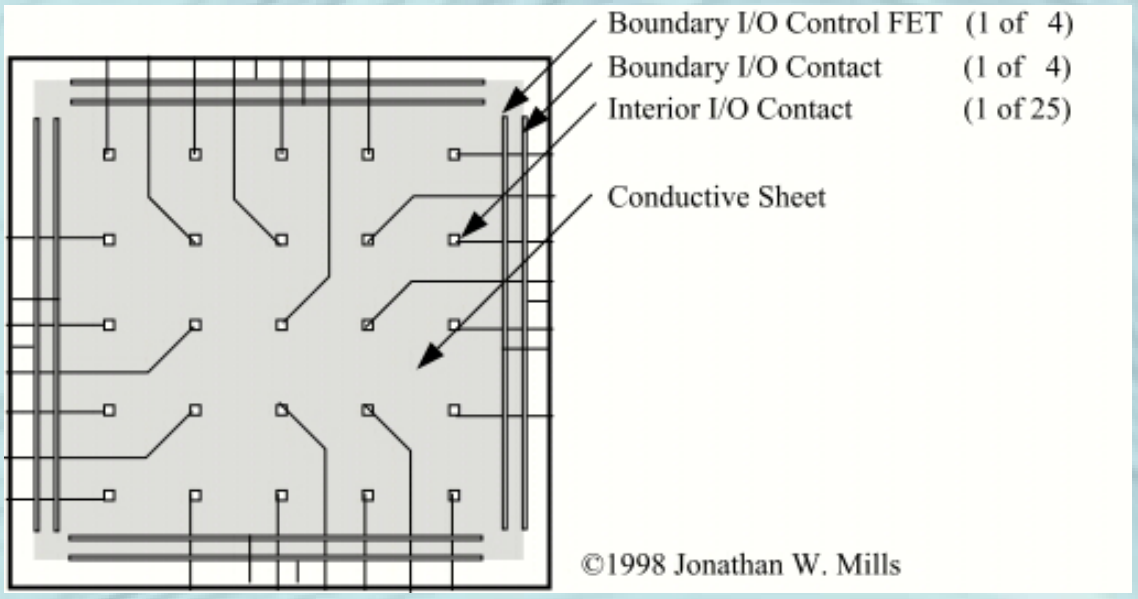
Continuous-valued Processor

- Processor consists of an array of pins inserted into a resistive sheet
- Resistive sheets have been used for half a century (Karplus 1958)
- A variety of materials are acceptable for use in the resistive sheet. Examples are:
  - Conductive foam
  - Conductive polymer
  - Silicon
  - Jello ®

EAC Foam Processor



EAC Silicon Processor



Chip is 1mm x 1mm lightly doped silicon

Jell-O® Brand Gelatin: 3-D Processing

Prototype for injection molded & laser polymerized processors

Extended Analog Computers

- What EAC processors *don't* have:
  - Potentiometers
  - Operational amplifiers
  - RAM
  - ROM
  - Programs
  - Clocks
- What EACs *do*
  - Maximum throughput when solving a Laplacian PDE is about 10^6 – 10^8 PDEs, after configuration

Architecture Comparison

Digital	**Analog**
Inherent bottleneck	Inherently no bottleneck
Sequential processor	Parallel processor
Internally fixed precision	Externally fixed precision
Precision increases temporally	Precision increases spatially
Explicit error-correction (coding)	Implicit error-correction (structure)

Programming/Configuring

Digital	**Analog**
Algorithms	Analogies
Many simple instructions	Few complex instructions
Programming model is modular and temporal	Programming model is holistic and spatial
Lexical (tokens)	Visual (whole systems)

Computing Paradigm: **Analogy**

An analogy is a specific relationship binding a computer architecture to nature. It is restricted to devices that:

- Don't need to be programmed
- May need to be configured

A configuration specifies the structure of functional elements:

- Spatial arrangement
- Inputs and outputs
- Means of measuring or observing

Applications

Digital	**Analog**
Exact results	Inexact results
Precision is mandatory	Imprecision can be tolerated
Parallelism is often challenging	Parallelism is often trivial
Speed of computation is valued and sought after	Speed of computation is so fast it can be “wasted”
Simple applications are trivial	Simple applications can be surprisingly challenging
Pseudo-random algorithms	Randomness is inherent

Evolutionary Analog Computing

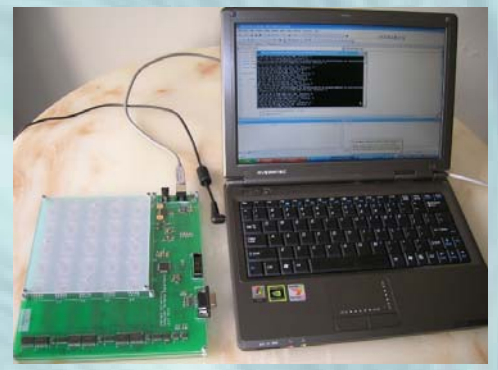
- Swarm intelligence or other evolutionary computation method is used to develop overlays for extended analog computer
- Analog microcontrollers are feasible
  - Can be totally analog
  - Can utilize digital I/O if desirable
- Analog/digital hybrid computers are feasible
  - Some tasks done by analog, some by digital processors
- Large 2D and 3D arrays of analog and hybrid configurations feasible

Advantages of Implementation

- Cheaper – Technology is less complex with fewer components; eliminates need for some digital and A/D and D/A circuitry
- More reliable – Eliminates need for some digital and A/D and D/A circuitry; no RAM, ROM, or code in purely analog microcontroller
- Faster – Basic calculation time in femtoseconds; continuous processing is highly parallel.
- Less subject to noise and degradation

Potential Application Areas

- Controllers
- Central processors
- Monitors
- Dynamic optimizers
- Diagnostic systems
- Classifiers
- ?



Military Application: Many on Many AEA EW Resource Allocation Optimization

- EW scenario
  - Airborne electronic attack
  - Many on many optimization
  - Near real time
- Sponsor: NAWCWD Point Mugu, CA

Human-Swarm Interaction

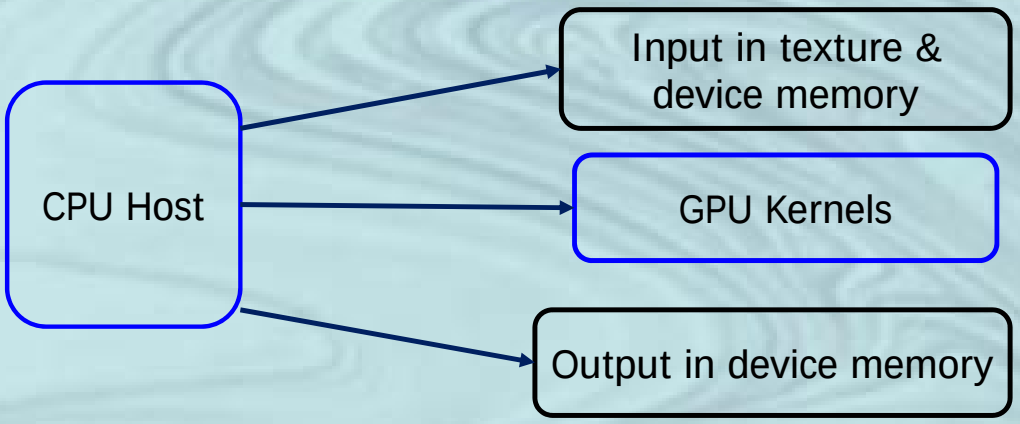
How do humans and swarms interact?

- Humans *are* swarms
- The human acts as a particle.
- The human serves as an observer/supervisor.
- The human works in the loop as part of the fitness feedback.
- The human serves as coordinator.
- Humans are linked to the computation swarm via biomedical sensors

Conclusions:

1. The combination of a human-swarm team has advantages in certain environments, such as dynamic decision making tasks.
2. The team approach can combine computer computational power with human intuitive knowledge to provide fast response for dynamic and complex tasks.

Parallel Swarms on Graphics Processing Units Uses the computer's CPU and an added GPU

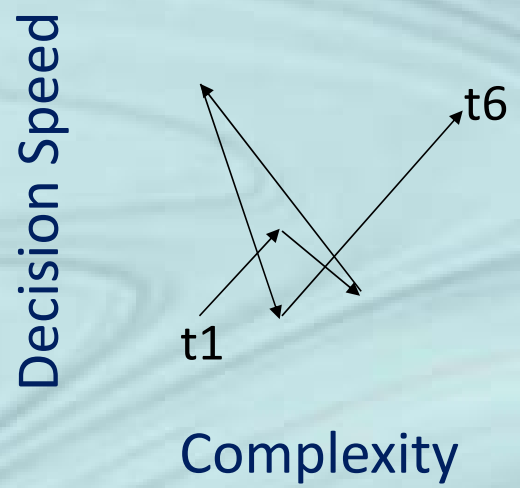


GPU with CUDA technology can process thousands of threads simultaneously, thus it can be used as a general purpose parallel machine.

- The computation time is significantly reduced by GPU acceleration (10-1,000 times faster)
- GPU framework provides an economical platform for parallelization of particle swarm implementation.
- Continuing development goal: 10,000 times speedup.

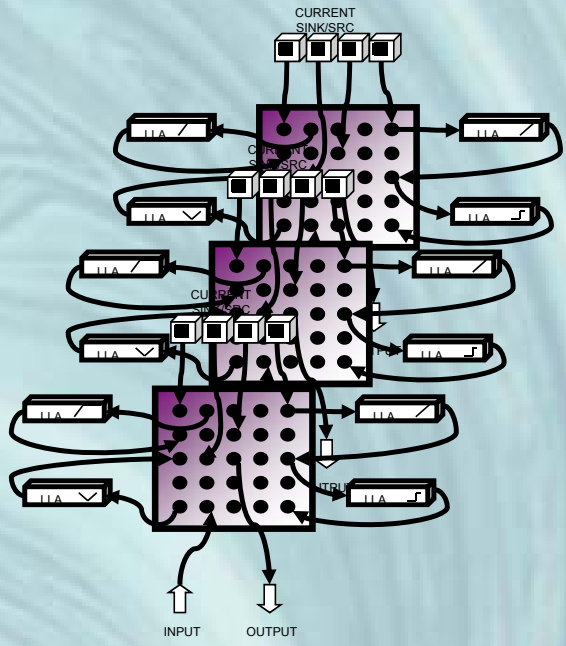
Human-Swarm Interaction:
Real-time Optimization of Human/Swarm Ratio

What combination of human and computational swarm is optimum?
In general, what combination of resources is optimum?



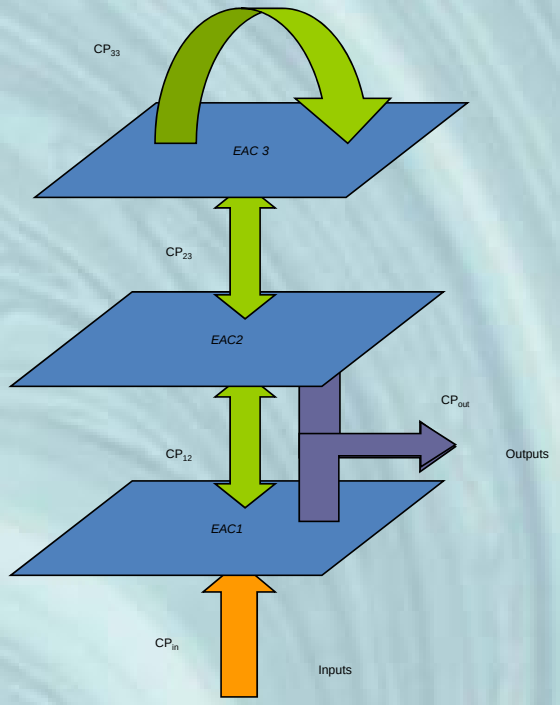
The Evolution of Intelligence Using Extended Analog Computing

- Layers of EACs can be combined in ways inspired by the layers of human cortex
- The layered system is then configured by swarm intelligence to give it properties that fit it to be used as smart matter, implementing class-specific elements not found in nature, yet that draw on natural principles, and are even more adaptive, robust and self-evolving than other systems.



The Evolution of Intelligence Using Extended Analog Computing The Super EAC

- This “super EAC” with many nodes will be configured to “look at itself” as it operates, and as a result of that introspection, modify its configuration to adapt to conditions.
- It can do this because so much of the computation is implicit, it is robust and tolerant of imprecise data, and because of its small size.
- The system’s intelligence will evolve as a result of interacting in an environment of functional components that represent the system’s model of the world. The development of this embedding environment is a fundamental part of the research.
- Note that this environment will co-evolve with the intelligent system, and that the form the intelligent system will assume will be determined by the physics of the embedding environment.
- The interaction between the two systems, proto-intelligent and environment, produces intelligence. It is not engineered by nature or humans.



Blended Intelligence

Blend:

Mix (a substance) with another substance so that they combine together as a mass where substances are indistinguishable

Blended Intelligence:

Intelligent behavior resulting from a blend of carbon-based and silicon-based subsystems in which the contributions of the subsystems are constantly adapting to complex and dynamic environments such that the intelligent behavior cannot be ascribed to specific subsystem contributions

Swarm/Human Blended Intelligence Workshop

Focus: Computational swarm intelligence R&D areas involving human/swarm interactions.

Topics:

- **Human controlled/directed swarms**
- **Humans supported fitness functions**
- **Swarms of humans**
- **Heterogeneous swarms**
- **Swarms observed/guided by humans**
- **Hybrid systems**
- **Gesture/voice controlled robot collectives**
- **Applications of blended intelligence**
- **Multiple platform algorithms**

October 21-23, 2016 in Cleveland, Ohio

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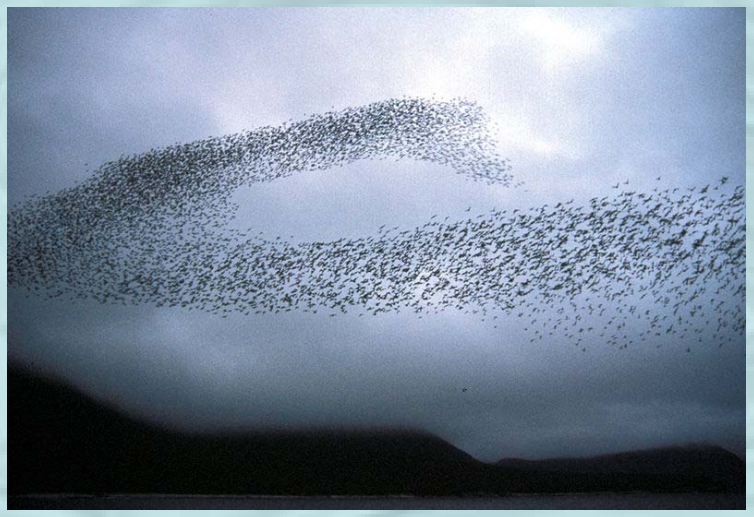
Thanks for your attention



May the swarm be with you!

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