Field-based Coordination

Franco Zambonelli & Marco Mamei
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Outline

○ Part 1: What is Field-based Coordination
  ● Definitions
  ● General aspects of field-based coordination
  ● Fields, self-organization, and stigmergy

○ Part 2: Examples of Field-based Coordination in Nature
  ● Gravitational systems
  ● Flocking in birds and fishes
  ● Wolves surrounding a prey
  ● Morphogenesis
  ● Modeling Fields

○ Part 3: Applications of Field-based Coordination in Distributed Systems Engineering
  ● Location-awareness
  ● Motion coordination
  ● Self-assembly

○ Part 4: Programming Field-based Coordination
  ● The TOTA Approach
  ● Examples of TOTA applications

○ Conclusions and Open Issues
Part 1

- What is Field-based Coordination
What is Field-based Coordination

- Field-based coordination is a physically-inspired indirect form of coordination
  - The space in which “agents” live is spread by sorts of force fields
    - E.g., gravitational fields, electromagnetic fields, chemical fields
  - Agents in their turn can contribute to spreading fields in space
    - E.g., the same as masses contribute to gravitational fields
  - Agents are affected in their activities by the locally perceived fields (type and strength)
    - E.g., the same as masses are attracted by gravitational fields
  - Fields are automatically updated to reflect the actual conditions
    - E.g., the same as gravity changes as planets move
What are “Agents” in Field-based Coordination

- Where talking about field-based coordination we will refer to the term “agent” to refer to
  - Any kind of autonomous entity situated in an environment
  - Sensing and effecting the environment via fields
  - Thus indirectly interacting with each other

- Examples
  - Animals
  - Software processes and software agents on a network
  - Mobile devices and sensor networks
  - Humans
  - Robots
What is “Environment” in Field-based Coordination

- When talking about “environment” in field-based coordination we generally refer to
  - The “space” in which agents execute
  - The “space” in which fields propagate
  - It is mostly an abstraction that assume actual meaning in actual examples

- Examples
  - A landscape in which animals live and interact
  - A network
  - A building in which humans and robots live
What are Fields?

- Assuming the presence of an environment
  - Fields are “distributed properties” of that environment
  - Describing “something” related to that environment in a distributed way
- Examples
  - The gravitational field is a property of space somewhat describing the structure of masses around
  - The pressure field is a property of the atmosphere describing the density of the air
- More in general, given
  - An metric environment $E$ (i.e., an environment whose points can be somewhat mapped in terms of some system of coordinates $X$)
  - A field $F$ can be defined as a function mapping a set of value over the coordinates of the environment $V = F(X)$, $X \in E$
Example of a Field over a Network

- Given a specific node of a network
  - We can imagine having a field that spread from that node and
  - Propagates over the network with a local value that increases each hop while traveling the network
There are several possibilities about spreading fields

- Fields can be an intrinsic property of space, independent of the presence of agent (e.g., pressure in atmosphere)
- Fields can be spread by agents, and different agents can spread different types of fields independently (e.g., a cry)
- A field can be an aggregation of different fields spread by individual agents (e.g., gravity)
Sensing Fields (1)

- In general, in field-based coordination we assume (as in nature) only strictly local sensing capabilities
  - An agent can perceive the local value of a field, not the overall distributed structure of a field
  - At least, it can perceive the local gradient of the field (i.e., in which direction it grows and how must it grows)
- This is very important in distributed systems because
  - It does not require global communications
  - It promotes scalability (what the agent can sense is independent of the actual “size” of the environment)
  - It promotes decoupling (the agent sense the field but do not care about who or what causes it)
Sensing Fields (2)

- The same field, spread by the orange agent and sensed by two green agents
  - At different places
  - And so with different values
Fields and Context-Awareness

- To some extent, fields represent a way to spread contextual information over a network
  - The presence of mass in the case of gravitational fields
  - The presence of some data or of some agent doing something in the case of computational fields
  - The presence of an agent at a specific distance in the network
- Clearly, this is a partial information
  - I only know there is an agent somewhere at distance “3”
  - And if I can sense the gradient I can perceive the direction in which it is
- But it is obtained in a very effective way, at very low local costs!
Fields as Distributed Data Structures

- To some extent, fields can be considered as a specific type of structured data
  - The structure is distributed
  - The same “information” is distributed on different regions of an environment
  - The information has a meaning that depend on the place on which it is perceived
  - And thus it varies to reflect in different regions the same meaning
- In the example of the network field
  - The meaning could be the distance from an agent
  - And thus the value has to change as the fields propagate farther from the source agent
Dynamics of Fields (1)

- Fields are expected to continuously reflect the actual state of what they represent
  - To reflect changes or movements of the originating agents
  - To reflect changes in the environment
- Examples
  - The gravitational fields of a star changes as it explodes or moves
  - The actual gravitational fields in a point of space depend on the position of all nearby masses
  - The structure of the network field should change if the structure of the network changes (due to, e.g., dismissing or mobility of nodes)
Dynamics of Fields (2)

- The node with the source agent moves
- And the field is updated
Dynamics of Fields (3)

- The node with the source agent moves
- And the field is updated
Fields and Adaptive Self-organization

- When agents rely on the local perception of fields for their activities
  - An agent locally perceives fields propagated by other agents
  - It may consequently change the structure of fields it owns propagates
- This implies the intrinsic presence of feedback cycles
  - Which could be positive
  - Or negative
  - And which in any case we already know are the basic ingredients for adaptive self-organization
- Adaptive self-organization with fields
  - Adaptivity because fields change to reflect changes in the environment (fields represent dynamic contextual information)
  - Self-organization because fields are a form of stigmergic coordination
Field-based Coordination and Stigmergy

- Field-based coordination is a specific type of stigmergic coordination
  - It is an indirect form of coordination
  - Fields represent property of the environment
  - Agents can affect the environment by spreading fields
  - Agents are affected by the environment, i.e., by the fields that are in it
- We will see that pheromones and fields are strictly related
  - After all, pheromones can be considered as sorts of “slow” fields
  - Thus, we will be able to implement pheromones with fields
  - Sometimes, the distinction between pheromones and field will be rather blurred
Part 2

- Field-based Self-Organization in Nature
  - And field modeling...
Gravitation, of Course...

- Well, gravity is field-based coordination
  - Is there self-organization?
- Yes, and indeed gravitational system exhibits all the possible status of dynamical systems
  - Equilibrium
    - All masses collapse into a single mass
  - Periodic Cycles
    - The regular orbiting of a mass around another
  - Self-organization (“edge of chaos”)
    - Consider the asteroids belt
      - It is rather “stable” and exhibit an overall organized, persistent, and adaptive, “shape”
      - Still, the movement of asteroids within is by no means periodic of stable
      - It is a system at the edges of chaos
  - Chaos (e.g., clusters of isolated asteroids)
    - Indeed, even a small number of isolated asteroids of similar mass moves around each other in a chaotic way
Flocking

- Birds and Fishes, as well as several other species, move in groups in a rather organized and ordered way
  - There is no leader in general
  - There is not agreement
  - Animals per se are not so intelligent
- So how does it work such expression of swarm intelligence?
  - Very similar to humans escaping fires
Mechanisms of Flocking

- Two possible explanations, same results

- 1. They do so because they want to stay together
   - possible explaining mechanism for each bird
     - Target closest bird
     - Get at a specific distance from it
     - Match its speed and direction
   - But this assumes a sort of mimicking capabilities in bird

- 2. They do so because in that way their movements are more effective (as a cyclist knows well!)
   - Possible explaining mechanism for each bird
     - Just fly
     - Trying to always stay in the zone of lower pressure
   - This is a mechanism of field-based coordination
     - The pressure field of birds as they fly
     - Influences the fly of other birds
     - Ending up in organized patterns of movement
Field-based Flocking

- The pressure field generated by each bird has a form like that:

- A bird close to another bird will try to stay in the minimum
  - i.e., will be attracted by the field

- Overall, when birds get flying together, they will end up in regular grid formations

- See the NetLogo simulation
Sheep Surrounded by Wolves

- When wolves go preying and see a e.g., sheep
  - They do not simply try to capture it in a greedy way
  - Rather they circumvent the prey
  - And leave it not way of escaping
- Is this wolves’ intelligence or there are swarm intelligence mechanisms behind?
  - The behavior is isomorphic to that of insects collectively carrying big objects
  - So it is likely to be a swarm intelligence phenomenon
Mechanisms of Surrounding

- Very simple indeed
  - Wolves are attracted by the sheep
  - But repel each other (because of competition)
  - The result is surrounding!
- This can be easily modeled in terms of fields
  - Attractive force fields: the wolves tries to reach the minimum of a force field originated by the sheep, and having its minimum by the sheep
  - Repulsive force fields: the wolves tries to reach the minimum of the aggregated force field generated by wolves, and having its minimum at infinity
  - Of course, the sheep fields must dominate!
- Ah, and obviously
  - It is expected that the sheep will try to escape, being repelled by wolves’ fields
Field-based Surrounding

- The Sheep field and the wolves fields
- The resulting force that drives wolves movement is something like:

\[ \text{FORCE} = \text{sheep\_field} - \text{sum(wolves\_fields)} \]
Modeling Field-based Coordination

- In the previous examples, fields act as forces attracting/repelling animals
  - Coordination, in this case, is related to motion and position
    - **MOTION COORDINATION**
      - Fields influence the relative positions and movements of animals in the environment
- In these cases, it is possible to model field-based coordination in terms of a simple dynamical system in which:
  - Fields are modeled as functions of the position of the sources (i.e., of the animals but more in general of the agents)
  - The next position of animals/agents is determined by the composition of the fields that they sense at the current time in their current positions
  - This is simply a system of differential equations...
Modeling Fields

- Let’s express field as a function of time and space (i.e., position of the source agent)
  - E.g. the Flock field

\[ d = \sqrt{(x - X_B^i)^2 + (y - Y_B^i)^2} \]

\[ FLOCK_i(x, y, t) = d^4 - 2a^2 \cdot d^2 \]
The Coordination Field

- In general, agents do not direct their action based on a single field, but based on a combination of locally perceived field
- If the specific combination of these fields, that we call \textit{coordination field} (CF) that determines where the agent will go
- In the case of flocking, any agents tries to reach the minimum of all the locally perceived FLOCK fields
- Thus is operate based on a min combination of local FLOCK fields

\[ CF(x_1, x_2, \ldots, x_n, t) = f(\text{FIELD}_a, \text{FIELD}_b, \ldots, \text{FIELD}_n) \]

\[ CF(x, y, t) = \min (FLOCK_i(x, y, t) : i = 1, \ldots, n) \]
The Evolution Equations (1)

- Thus, the laws governing the movement of an agent \( i \) along the \( x_j \) direction are in the form below:

- Where the spatial derivative of the coordination field expresses the fact that an agent follows the gradient of the coordination field.

\[
\frac{dx^i_j}{dt} = v \cdot \frac{\partial CF_i(x_1, x_2, ..., x_n, t)}{\partial x_j}(x^i_1, x^i_2, ..., x^i_n, t) \quad j = 1, 2, ..., n
\]
Thus, for an example in the 2-dimensional case, the evolution of the flocking behavior for an agent $i$ can be described by the following system of differential equations:

\[
\begin{align*}
\frac{dx_i}{dt} &= -\nu \frac{\partial \min (FLOCK_1, FLOCK_2, \ldots, FLOCK_n)}{\partial x} (x_i, y_i), \\
\frac{dy_i}{dt} &= -\nu \frac{\partial \min (FLOCK_1, FLOCK_2, \ldots, FLOCK_n)}{\partial y} (x_i, y_i).
\end{align*}
\]
Integrating the Equations

- Once the equations are defined
  - We can write them for each agent
  - And initialize them with the initial positions of the agents
  - Obtaining a global set of related differential equations

- The equations can be numerically solved by mathematical software tools to see the evolution of the system (i.e., the trajectories of agents in space)
  - Aside two examples for a flocking system with 4 agents in 2-d
  - With different initial conditions
Modeling Surrounding (1)

- The FIELD of wolves (pred)

\[
FIELD_i^{pred}(x, y, t) = 1 + k_p - k_p e^{-h_p((x - X_p) + (y - Y_p))}
\]

\[k_p, h_p > 0; \quad 1 + k_p - k_p e^{-2h_p} \approx 1\]

- The FIELD of sheeps (prey) is simply the opposite of that of wolves...
Modeling Surrounding (2)

- Coordination field of wolves \((pred)\)

\[
CF_i^{pred}(x, y, t) = FIELD^{prey}(x, y, t) + \sum_{j=1, j\neq i}^{n} - FIELD_j^{pred}(x, y, t)
\]

- Coordination field of sheeps \((prey)\)

\[
CF^{prey}(x, y, t) = \sum_{i=1}^{n} - FIELD_i^{pred}(x, y, t)
\]
Modeling Surrounding (3)

- The overall equations

\[
\begin{align*}
\frac{dx_{\text{prey}}}{dt} &= -v_{\text{prey}} \frac{\partial CF_{\text{prey}}(x, y, t)}{\partial x} (x_{\text{prey}}, y_{\text{prey}}) \\
\frac{dy_{\text{prey}}}{dt} &= -v_{\text{prey}} \frac{\partial CF_{\text{prey}}(x, y, t)}{\partial y} (x_{\text{prey}}, y_{\text{prey}}) \\
\frac{dx_{i_{\text{pred}}}}{dt} &= -v_{\text{pred}} \frac{\partial CF_{i_{\text{pred}}}(x, y, t)}{\partial x} (x_{i_{\text{pred}}}, y_{i_{\text{pred}}}) \quad i = 1, 2, \ldots, n \\
\frac{dy_{i_{\text{pred}}}}{dt} &= -v_{\text{pred}} \frac{\partial CF_{i_{\text{pred}}}(x, y, t)}{\partial y} (x_{i_{\text{pred}}}, y_{i_{\text{pred}}}) \quad i = 1, 2, \ldots, n
\end{align*}
\]
Modeling Surrounding (4)

- The Integrated equations (compared with the no-surrounding case)
Why Modeling?

- It can be useful to understand, prior to developing a system, and prior to build a simulation, if an approach make sense
  - The mathematical simulation, even if unrealistic, or developed with a limited number of agent, can outline specific problems of a solution
- In any case, this must be coupled with simulation, including a larger number of agents
Motion vs. Activity

- So far, in the examples, fields have been used to determine the movement of agents
  - Pure motion coordination
  - The reaction of agents in perceiving fields was simply that of following the gradient of the fields
- However, field-based coordination may be more general
  - The perception of a specific field with a specific value by an agent
  - Can cause it to change its internal state
  - Can make it react to emit other types of fields or to inhibit the propagation of some fields
- In other words, fields can be used to enforce coordination of activities other than of motion
- For example, in morphogenesis...
Morphogenesis

- Morphos + Genesis = Shape Birth
  - The process by which something grows into a specific shape
- This is definitely one of the biggest open issues in science
  - How an embryo grows?
  - How cells understand how to differentiate each other?
  - How can they understand where to grow and when to stop?
- What is being understood is that a field-based coordination model is behind all (most of) that
Morphogen Gradients = Fields

- Cells emit chemicals
  - Which diffuse from cell to cell
  - As in the example of the field spreading in a network hop by hop
- The behavior of a cells, that is
  - The activation/deactivation of specific genes and – thus – the type of cell it has to become and the way it must reproduce
  - The type of chemicals that the cell, in its turn has to diffuse
- Is determined by the perceived concentration of morphogen gradients
  - The same as in field-based coordination the actions of an agent are determined by its local perception of field
Fields vs. Pheromones

- Pheromones are something that gets deposited in an environment
  - And there rest
  - Slowly diffusing
  - And slowly evaporating

- Fields, on the other hand, are something that exists because some entities are propagating them
  - They exist until they get propagated
  - They immediately change when the conditions of propagation change

- Clearly, it is possible to conceive a field
  - With a very very slow propagation
  - With a very very slow reaction time in changing

- In that case, the field would become a pheromone
  - i.e., it is possible to model pheromones in terms of “slow” fields

- In any case, it is important to note that for both fields and pheromones
  - The environment plays a vital role in sustaining propagation and updates
Part 3

- Applications of Field-based Coordination
The Applications are Various…

- **Location-awareness**
  - As a way to distribute and access contextual, location-dependent, information
  - In pervasive and mobile computing scenarios, as well as in sensor networks

- **Motion Coordination**
  - For mobile users, robots, or software agents

- **Videogames**
  - Using fields to drive characters

- **Self-assembly**
  - As a way to mimic morphogen gradients and produce self-assembly artifacts in which parts can self-differentiate
  - This will be dealt with separately, in another lecture
A Scenario: a Big Museum

- A big museum, such as the Louvre
  - Difficult to explore (where the hell is Mona Lisa?)
  - With a structure and topology often varying (due to temporary exhibitions or restructuring)
  - With a lot of information to access about art pieces
- Let us assume that
  - There is a network running in the museum whose topology mimic the topology of the museum (if not, the museum topology can be simply mapped as an overlay over the physical network)
    - This could also be an-hoc wireless network, to avoid the costs and the damages of wiring
  - Each piece of art has an internal device with info about it, integrated in the network
  - Each users and tourist guide has a PDA via which to access the network from the closest access point
- The scenario, in any case, is representative of a wider range of distributed applications...
Location-awareness in the Museum

- Fields, propagated in the museum by tourists, or by museum guards, can be used to have
  - Tourists discover where a specific piece of art is
  - Tourists and Guards discover where other tourists/guards are
  - Etc.
- To this end, we can assume that each tourist and each guard
  - Diffuse a PERSON PRESENCE field, propagating in the museum network with an hop-increasing value, and having also as a content the ID of the person
Discovering Other People

- Based on the PERSON PRESENCE field, any user can simply
  - Perceive the corresponding field (with the specific ID) to understand distance and direction
  - Eventually, decide to follow the field to reach that person
Discovering Pieces of Art (1)

- If each piece of art diffuse a similar field
  - Any person can locally read the location of that piece of art
- When a person is interested and reads the local field of a specific piece of art
  - Can eventually send a message-field to that piece of art to discover further information
  - The message field propagates by following downhill the field of the piece of art, and will reach it as a ball down a surface
  - When the piece of art receive the message field, can react by sending back to the user information
Discovering Pieces of Art (2)

- As an alternative solution
- To avoid pieces of art diffuse their fields in the whole museum, one can think at
  - The pieces of art have no fields diffused
- But can react to “Query fields” diffused by users
  - When a user wants to know something about a piece of art
  - Spread a query field that increase hop-by-hop as it travels
  - The query field reach the specific piece of art
  - Which react by spreading and “Answer field” that follows downhill the query until it reaches back the user
Where is Mona Lisa?
Propagate a Query Field

*Query Field*
*Content* = (description, distance)
*Prop* = (propagate to all peers hop by hop, increasing the “distance” field by one at every hop)
Where is Mona Lisa?
The Answer Follows Query Field Downhill

Answer field
Content = (description, location, distance)
Prop = (propagate following downhill the “distance” of the associated query field, incrementing distance value by one at every hop)
Location-dependent Computing

- In general, one can think at
  - Limiting the propagation of fields at specific distances
  - Directing the propagation in specific directions
- In that way, it is possible to
  - Search information in specific locations
  - Avoid being discovered from “too far”
  - Very useful in mobile and ubiquitous computing
- Example, as a tourist in a big town who ask the wireless city network for good Chinese restaurants, I want to know about close restaurants, not about all restaurants in other – far – parts of the town
Motion Coordination

- By using the introduced PERSON PRESENCE field, one can think at coordinating the activities of tourists and guards, as they move in the museum
  - Meeting at a specific place, using PRESENCE FIELDS as gravitational fields (the meeting place will end up being the center of gravity, minimizing global efforts for meeting)
  - For guards, finding a children lost in the museum, or a thief using PRESENCE FIELDS to implement
  - Moving in formation (e.g., for guards) using FLOCK fields similar to that of flocking in birds
- What is interesting is that the resulting behavior is extremely adaptive
  - There is no need to know a priori the map of the museum
  - It is the propagation of fields that automatically adapt to the map
  - And enables any form of motion coordination, in an adaptive and environment independent way
Examples of Motion Coordination

- Meeting
Examples of Motion Coordination

- Surrounding
Examples of Motion Coordination

- Moving in Formation
Adaptivity of Motion Coordination

- The algorithms work the same independently of the museum map
  - Without changing a bit in the code of agents
  - E.g., for meetings
Fields in Videogames

- Field-based approaches can be exploited in videogames to drive the actions of characters
  - In “The Sims” fields drive characters toward what they want (“I am hungry!” → let’s follow the Fridge field)
  - In Quake, we have integrated field-based motion coordination as a strategy to improve cooperative fighting in the “bad boys” (Mamei and Zambonelli, 2004)
Part 4

- Programming Field-based Coordination
What is Required?

- To program and deploy field-based coordinated application we need
- Some **network infrastructure** to be used as the space in which to propagate fields
  - The Internet, an ad-hoc network, a pervasive network, a sensor network
- A fully distributed **middleware (P2P)**, providing the following minimal services
  - A local dataspace where to store the value of fields as they get propagated, and to have application agents access the local values of fields
  - Communication mechanisms, to have the various middleware communicate with each other and enable propagation of fields in the network
  - System-level event-based mechanisms, to understand how the network situation changes and update fields accordingly
  - Application level event-based mechanisms, to have application agents understand when fields arrive and/or when they change
The TOTA Approach

- A tuple-based system for field-based coordination in dynamic networks
  - Implemented for PC, PDAs, Lego Robot
  - Mamei and Zambonelli, 2003-2005
- Extends traditional tuple-based coordination models with a model in which
  - Tuples are not stored in a single tuple space
  - Tuples, other than a content $C$ as usual, can have their own propagation rules $P$
  - The propagation rule can specify how the content of the tuple can change during propagation

$$T=(C, P)$$
TOTA Key Characteristics

- Fields are represented by tuples
  - This enables to include some specific content with fields
  - The programmer can invent and program its own types of fields/tuples
- Tuple libraries are available
  - To exploit with minimal efforts a variety of different types of fields
- Propagation rules are fully programmable
  - This enables programmers to decide how and to which extent a field-tuple should propagate
- Maintenance of the distributed field structure is automatically preserved
  - The middleware automatically react to changes in networks and applications updating the structure of propagated fields/tuples
TOTA Middleware Architecture

Application Agents Exploiting Field-based Coordination

- EVENT INTERFACE
- TOTA API
- TOTA ENGINE
- STORED TUPLES

Operating System

Network

To/From neighbor TOTA middlewares

This is used by agents to capture events

This is used to store field-tuples

This structure is replicated in each node of the network

These are the primitives to access the services of the TOTA middleware

The Network
The TOTA API

void inject (TotaTuple tuple);
// inject a tuple-field in the network
// the middleware will automatically propagate it on the basis of
// propagation rules defined within the tuple itself

Vector read (Tuple template);
// read local tuples matching the template

Vector readOneHop (Tuple template);
// read also the tuples of the neighbourhood, to evaluate gradients

Tuple keyrd (Tuple template);
Vector keyrdOneHop (Tuple template);

Vector delete (Tuple template);
// delete a local tuple

void subscribe (Tuple template, ReactiveComponent comp, String rct);
void unsubscribe (Tuple template, ReactiveComponent comp);
// tu subscribe/unsubscribe to event occurring in the tuple space
// related to the arrival or change of field-tuples
Programming TOTA Applications

- Programming TOTA coordinated applications basically means to
- Programming the tuples
  - i.e. specifying the tuple classes in terms of the type of content they have to include, their propagation rules, and their maintenance rules
- Programming the agents
  - That is, the code in which agents exploit the TOTA API, create tuple instances and propagate them in the network, and read tuples from the local tuples space
abstract class TotaTuple {
protected TotaInterface tota;
/* the state is the tuple content */
public void init(TotaInterface tota) {
  // the init method initialize the tuple
  this.tota = tota;
}
public abstract void propagate();
// the propagate method is abstract
// has to be implemented by subclasses
// to specify how the tuple should propagate
public void react(String react, String event) {
  // this method specify how the tuple should
  // react, e.g., maintain, in response to
  // network dynamic
}
The TOTA Tuples Library

Partial view of the TOTA tuple hierarchy/library

- **TotaTuple**
  - The basic “everywhere” propagation rule for tuples

- **StructureTuple**
  - Tuples that propagate everywhere in the network based on localization information (e.g., GPS)

- **MessageTuple**
  - Tuples that do not get stored but simply “travels” all the networks as a wave

- **HopTuple**
  - Tuples that propagate in the network, hop-by-hop, whose content can change during propagation, and that are self-maintained by the middleware

- **SpaceTuple**
  - Tuples that propagate everywhere in the network based on localization information (e.g., GPS)
Tuple Programming

Other than defining its content, programming a tuple may imply programming its propagation rule, which we suggest structuring as below and implementing some of the sub-method specified below:

```java
public final void propagate() {
    if(decideEnter()) {
        boolean prop = decidePropagate();
        changeTupleContent();
        makeSubscriptions();
        tota.store(this);
        if(prop)
            propagate();
    }
}
```
The HotTuple Class

Tuple that propagates in the whole network and simply increment a **hop** value by one at each hop in the network

```java
public class HopTuple extends StructureTuple {
    public int hop = 0;
    public boolean decideEnter() {
        super.decideEnter();
        NMGradient prev = (NMGradient)tota.keyrd(this);
        return (prev == null || prev.hop > (this.hop + 1));
    }
    protected void changeTupleContent() {
        super.changeTupleContent();
        hop++;
    }
}
```
The DownhillTuple Class

A tuple that propagates by following downhill the gradient of an already stored HopTuple (it propagates in a single path across the descent of an HopTuple)

```java
public class DownhillTuple extends StructureTuple {
    public int oldVal = 9999; HopTuple trail;
    public boolean decideEnter() {
        super.decideEnter();
        int val = getGradientValue();
        if(val < oldVal) {
            oldVal = val; return true;
        } else return false;
    }
    private int getGradientValue() {
        Vector v = tota.read(trail);
        int min = 9999;
        for(int i=0; i<v.size(); i++) {
            HopTuple gt =(HopTuple)v.get(i);
            if(min > gt.hop) min = gt.hop;
        }
        return min;
    }
}
```
Programming TOTA Agents

- Let’s refer to the example of a tourist in a museum that wants to know where “Mona Lisa” is, and wants to get information about.
- The agent in the user PDA
  - inject a Query field in the form of a *HopTuple*, which propagates in the network, and then wait for the income of some Answer tuple.
- The agent of the Mona Lisa picture
  - Can be programmed to react to incoming Query tuples.
  - By injecting an Answer tuple in the form of a *DownhillTuple* that follows the path of the Query tuple to reach back the user.
public class UserAgent implements AgentInterface {
    private TotaMiddleware tota;

    public void start() {
        HopTuple query = new HopTuple();
        query.setContent("Monna Lisa");
        tota.inject(query);
        DownhillTuple answer = new DownhillTuple();
        answer.setContent("Monna Lisa *");
        tota.subscribe(answer, this, "display");
    }

    public void react(String reaction, String event) {
        if(reaction.equalsIgnoreCase("display ")) {
            System.out.println("Monna Lisa:" + event);
        }
    }
}
public class MonaLisaAgent implements AgentInterface {
    private TotaMiddleware tota;
    private String description, location;

    public void start() {
        // subscribe to query. Queries will be conveyed in HopTuple
        HopTuple query = new HopTuple();
        query.setContent(description);
        tota.subscribe(query, this, "answerQuery");
    }

    /* code of the reaction, here it injects the answer tuple. The
    answer will be conveyed in a DownhillTuple following the
    query. The query is here referenced as HopTuple event */
    public void answerQuery (OneHopIncTuple event) {
        DownhillTuple answer = new DownhillTuple(event);
        answer.setContent(description + " " + location);
        tota.inject(answer);
    }
}
A Snapshot of TOTA Implementations

Simulator

PDA

Lego Robot
Tuple Maintenance

- Tuples must be **propagated** and **maintained**.
- Propagation is based on a simple hop-by-hop epidemic mechanism.
- Maintenance is based on local perception of network events and re-shaping of the propagated structure accordingly.
Conclusions and Open Issues

- Field-based coordination as a peculiar form of stigmergy
  - Promoting context-awareness
  - Promoting self-organization
- That finds several useful applications
  - Supporting motion coordination
  - As well as various applications in pervasive computing
- There are several issues that would be worth exploring
  - Exploiting fields for P2P computing
  - Exploiting fields for multiagent coalitions and for computational economies
  - Using computational fields to understand the mechanisms of morphogenesis