Spray Computers:
Explorations in Self-organization for Pervasive Computing

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Goals of the Seminar

- Exploring self-organization
  - As a novel approach to distributed systems engineering
  - As a tool to deploy and maintain complex applications in complex networks
- OUTLINE
  - A vision of the future:
    - enabling technologies & potential applications
  - A case study: the cloak of invisibility
    - To learn about: basic principles and techniques of self-organization: self-localization, adaptive routing in amorphous networks
  - Emergent behaviour in networks

A Vision of the Future: C.N.M. Everywhere

- A vision of the future (reasonable and maybe no longer so much visionary…)
- ***C***omputing everywhere and at every scale
  - In every room and object
  - At every scale (from nano- and micro-devices, to virtual super computers)
- ***N***etworking everywhere and at every scale
  - Small local micro-sensor networks
  - The ubiquitous and the embedded Internet
  - Personal area networks and very short-range radio communications
- ***M***obility everywhere and at every scale
  - We move with our laptops, PDAs and cell phones
  - Furniture can be moved around the house
  - Small wheeled micro-bots

C.N.M. Everywhere: the Big Scale

- World-wide networks (different levels)
  - Routers and IP nodes
  - The Web network
  - P2P Networks (e.g., Gnutella, Freenet)
- Millions of interconnected computer-based (or autonomous software) components
- Mobility….more and more….
  - Slow mobility (I connect my laptop from different places at different days)
  - Fast mobility (I want to stay connected while roaming…)

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C.N.M. Everywhere: the Medium Scale

- Computer-based objects
  - PDAs and cell phones
  - Intelligent hardware (e.g., fridges, washing machines, etc.)
  - Smart artifacts (e.g., smart doors, smart tables, etc.)
- Communication enabled
  - E.g., personal area networks (Bluetooth), IR, Wi-Fi
- Mobility
  - We move with carried-on objects
  - We move objects
  - Some objects move (e.g., cars)

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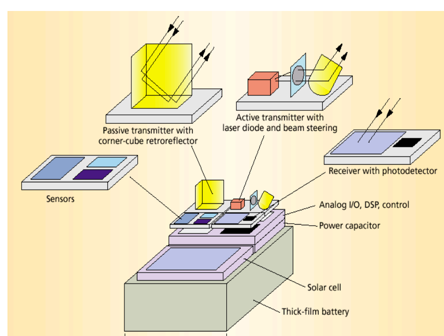
C.N.M. Everywhere: the Small Scale (1)

- Micro computer-based devices:
  - E.g., “smart dust”
  - 1mm^3 computer with optical I/O capabilities
  - IR or ultra-wide band short range communications
- Large scale production possible
  - Foreseen price << 1$



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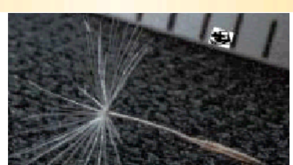

(from IEEE CiSE, 1997)

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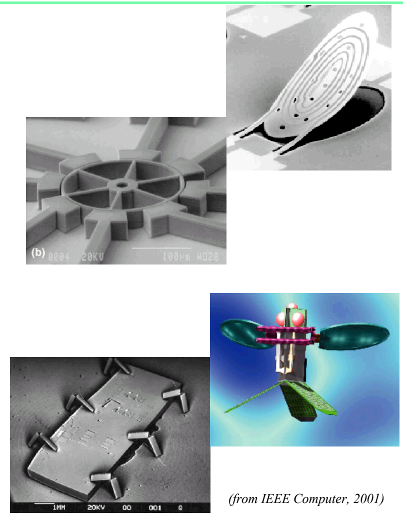
C.N.M. Everywhere: the Small Scale (2)

- MEMS
  - Specific mechanical actions (sensing of movement, pressure,)
  - Possibly coupled with limited computing and communication capabilities
- And micro-robots…
  - Mobile!



(from IEEE Computer, 2001)

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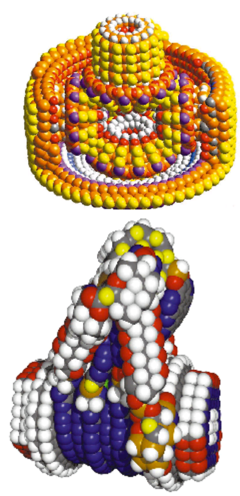
C.N.M. Everywhere: the Nano Scale

- Molecular Scale devices:
  - Capable of local sensing and local effecting
  - Interacting with each other via direct contact or by exploiting physical phenomena (diffusion, electromagnetic fields, etc…
  - Capable of movements
- Large scale production impossible today
  - Drexler's vision: molecular assemblers



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The Global Perspective

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- Altogether, a very huge networks:
  - Billions of interconnected computers, from micro to macro ones ("The embedded Internet")
  - e.g. IPv6 will make it possible to individually address each and every mm^2 on the earth surface….
- Characterized by dramatic dynamics at all scales
  - Nodes arriving, leaving, changing their location
  - E.g., Internet nodes and Web sites, cell-phones, micro-sensors
- And also at the level of software
  - New applications deployed at any time
  - intrinsic inter-dependencies between different applications

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The Vision of "Spray Computers"

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- Forget about traditional "deployment"
  - A component (and the associated software) cannot be "placed" in well-defined position in a network
  - The structure of the network cannot be engineered in any way
  - The evolution of the network cannot be exactly predicted
- Computers are deployed as in a "spraying" process

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Types of "Spray Computers"

- Micro-computers:
  - If we have << *1mm³* computers, we could indeed produce a paint or a spray
  - to physically distribute myriads of such components in an environment
- A "cloud" of persons with a PDA
  - Moving around and interacting via the PDAs $\rightarrow$ as particles moved by the wind
- The Internet
  - Node mobility
  - Virtual mobility of Services and ephemeral services (e.g., Gnutella)

Why Self Organization is Needed ?

- When networks and large, decentralized, and dynamics ("spray networks")
  - High complexity of software
    - very hard to be managed and engineered
  - Impossibility of direct control and configuration
    - Cannot control all of the sensors
    - Cannot control all the nodes of the Internet
  - Impossibility of direct maintenance
    - Cannot re-configure manually in the presence of faults or of dynamic changes
    - Application must not stop working and should preserve specific quality levels
- And even if we could
  - Economically unfeasible
    - Too high development and maintenance costs
  - Commercially unacceptable
    - Who wants a system which is always in need of configuration?

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What is Self-Organization?

- Components get “sprayed” and:
  - They recognize who and where they are (w.r.t. the other components)
  - They identify their specific task in the network (according to the who and where)
  - They start working in cooperation with the other components to achieve their task
  - The global goal/configuration is reached without any supervision
- Upon dynamic changes
  - They recognize such changes
  - And re-adapt the initial configuration to suit the new situation

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Applying Spray Computers…

- Given the availability of:
  - Theoretical models
  - Algorithms
  - Middleware infrastructures
  - Programming abstractions
  - Methodologies and tools
- For “spray computers”
  - i.e. strongly relying on self-organization
- A number of potential innovative applications can be conceived and deployed….

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Application Visions….

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- The "spray" self-organizing Web (that's already on the way…)
  - P2P access to data and services
  - Dynamic and self-healing re-structuring of links
  - Tolerating, e.g., mobility and faults
  - Relying on self-localization on virtual overlay network structures (e.g., Gnutella links)
- And more:
  - Emergence of communication languages and conventions
  - Emergence of peculiar highly optimized structures (e.g., small worlds and scale free)

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Application Visions….

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- Spray television
  - Micro computer-based emitters
  - To display TV programs and PC screens
  - Requires:
    - Self localization of components, and possibly distributed time synchronization
- Smart paintings
  - To display colors and various patterns on demand
  - Requires
    - Self localization of components, coordinated emergent behaviors

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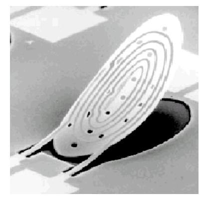
Application Visions….

- Active cereal boxes (remember “Minority Report”?)
  - Painted with optical micro-computers
  - Activated upon movement
  - Start animating a cartoon
  - Requires:
    - Self localization, time synchronization, emergent coordinated behaviors, self-differentiation
- Active pipelines
  - Micro components affecting fluid flow
  - And avoiding e.g., turbulence
  - Requires
    - Coordinated distributed sensing and coordinated movements



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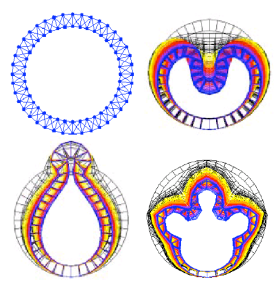
Application Visions….



(from Comm. ACM, May 2000)

- Self-assembly
  - Micro and nano-scale components
  - Capable of orchestrating their movement
  - So as to assume specific shapes
  - Adaptive and self-healing
- Amorphous computing
- Terminator T-1000

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The Chricton's Vision in "Prey"

- "Swarms" of nano component
  - Mixed organic and silicon-based material
  - Capable of flying by attaching to air molecules
  - Capable of self-assembly
  - Capable of collective self-organizing vision
  - Capable of collective sentient behavior
- Built by a complex self-organized systems of other micro-components
  - The "assemblers"
  - Capable of self-reproduction
- Is this really science fiction?

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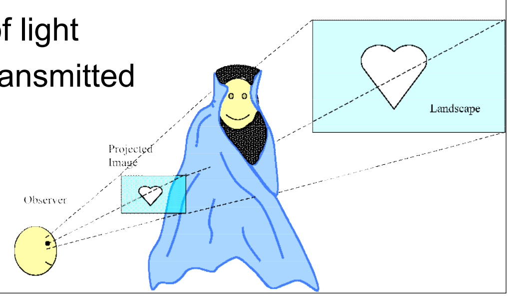
Case Study: The Cloak of Invisibility

- A fabric of small computing devices that
  - Gets densely painted on a tissue
  - Interact via short-range wireless comms.
  - Can sense and retransmit light emissions in a directional way
- So that:
  - Any blocked ray of light
  - Gets properly retransmitted



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Why 'The Cloak of Invisibility'?

- Fascinating application by itself, but….
- The software challenges to build such an artifact are archetypal for a whole range of other application scenarios:
  - self-localization
  - routing in amorphous and mobile networks
- Here we attempt to highlight these challenges
  - propose a conceptual solution to build the cloak (and other smart artifacts)
  - present a few key algorithms for "spray computers"

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The Clock of Invisibility: Structure of the Presentation

- Incremental presentation: from simple to complex
- The Invisible Wall
  - Provide invisibility for a regular shaped rigid object, from a single fixed point of observation
  - Key issues: 2-D localization, location-based routing
- The Invisible Object
  - Provide invisibility for a rigid object of whatever shape and from whatever point of observation
  - Key issues: 3-D self-localization, content-based routing
- The Cloak of Invisibility
  - Provide invisibility for a flexible fabric from whatever point of observation
  - Key issues: Dynamic re-localization, Routing on mobile ad-hoc networks

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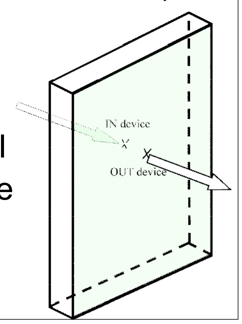
The Invisible Wall

- Paint the wall with densely packed micro devices
  - IN (light sensors) and OUT (light emitters) devices on the two sides, respectively
  - Computer-based
  - Communication-enabled (e.g., IR or radio-based)
- In the sensor network
  - Route messages (light information) from IN to OUT devices on the corresponding coordinates of the wall
  - So as to globally reproduce the image



Software Issues

- Let us assume the sensor and emitters are “painted” (or “sprayed” on the wall)
- To properly establish the IN and OUT pairs
  - devices must **determine their location** on the wall
  - Properties required:
    - **Decentralized and fully autonomous** process
    - **No direct human intervention**
- To route data from IN to OUT devices
  - Specific **routing algorithms** are required
  - Properties required:
    - **Fault-tolerance** (sensors can die or get out of power)
    - **Adaptivity** (we are not looking for a specific sensor, but for the best suited one, I.e., the one closest to the specific coordinates)

Self-Localization

- **(What is)** Devices in an amorphous sensor network determines their coordinates accordingly to a common reference frame
  - Two steps:
    - Determine the reference frame
    - Determine the location in the frame
- **(What is for)** Spatial coordination, mark data with spatial information, location-aware applications
  - In the cloak, **location-based routing**
  - Send this *color* to device at ***(x,y)*** **coordinates** on the other side of the wall

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Localization Principles

- Simple triangulation based mechanism
  - Rely on "beacons" to define a coordinate frame
    - 3 not-aligned beacons needed for a 2D frame,
    - 4 not-aligned beacons needed for a 3D frame.
  - Devices evaluate their distances from the beacons
    - Simple Euclidean considerations lead to the position
    - Distance "triangulation"
- Iterative triangulation
  - When not all devices can estimate their distance from the beacons (I.e., in the presence of short-range communications or obstacles)
    - The devices that have already determined their location
    - Can act as delegated beacons for other devices
    - And so on…

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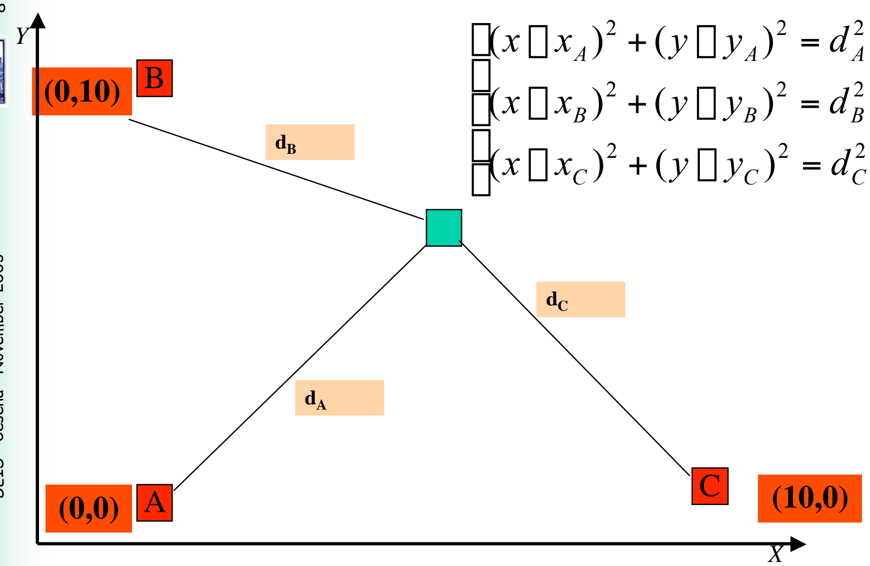
Beacon-based Localization: Example

$$\begin{cases}(x-x_A)^2+(y-y_A)^2=d_A^2\\(x-x_B)^2+(y-y_B)^2=d_B^2\\(x-x_C)^2+(y-y_C)^2=d_C^2\end{cases}$$



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Identifying Beacons

- External beacons
  - GPS (Global Positioning System)
    - Only outdoor
    - Expensive hardware
  - Wi-Fi access points
    - Reduced accuracy (meters)
    - Suitable for locating, e.g., persons in rooms, not for self-localization of small sensors networks
- Elected beacons
  - Cheap hardware
  - **Suitable to spray computers….**dense networks of peers:
    - Beacons are nodes as the other ones
    - Enable iterative localization

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Electing Beacons

- It is basically a "leader election" process
- External stimuli
  - Specific beacons are selected from the external of the network
  - Requires human intervention
  - Difficult for "sprayed" computers
- Autonomous Leader Election
  - Devices generates, e.g., a random number
  - These numbers get broadcasted in the network
  - After a while, the devices having generated the highest numbers will know they are the leaders

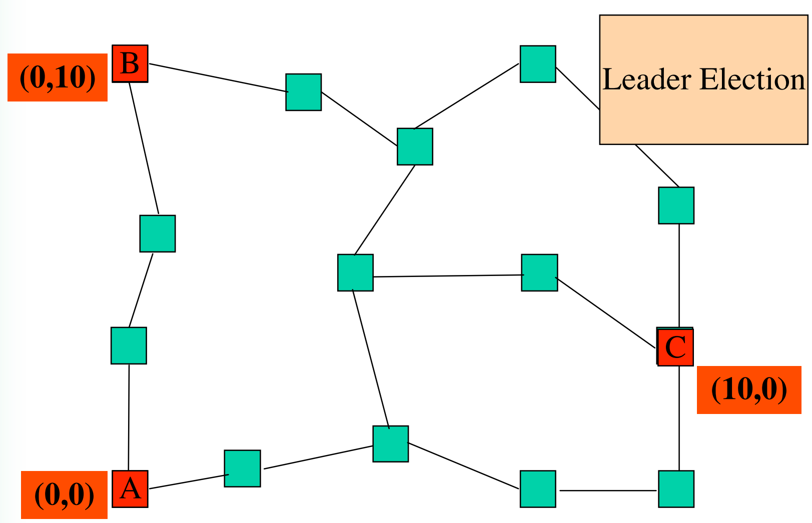
Estimating Distance from Beacons

- Principle
  - Beacons emits a signal to neighbor devices (e.g., those in the communication range)
  - Devices determines distance on the basis of specific properties of this signal
- Mechanisms
  - Signal attenuation (e.g., radio signal)
    - Not enough precision on short distances
  - Travel time of acoustic waves or phase displacement of IR waves
    - Could be more accurate (cm-scale obtained with acoustic waves and IPAQs)
    - Requires very accurate time synchronization (which is another challenging problem by its own)
  - **Density based approaches**

Density-based Distance Estimation

- Requires Devices
  - to be “dense” and to know their average density
  - to be able to send short-range signals to close devices
- Then
  - The beacon send a message to neighbors with a integer = 1, counting the number of hops the message has traveled
  - The signal is re-transmitted by each device after having incremented the counter
  - After a while, devices know their distance, in terms of hops, from the beacons
- Eventually
  - Triangulate and Calculate *Hops*AvgDist = PhysDist*
- Accuracy
  - Depends on average density: *Accuracy=AvgDist*
  - Requires at least 15 one-hop neighbors
  - Could be improved by multiple iterations

Example



Example

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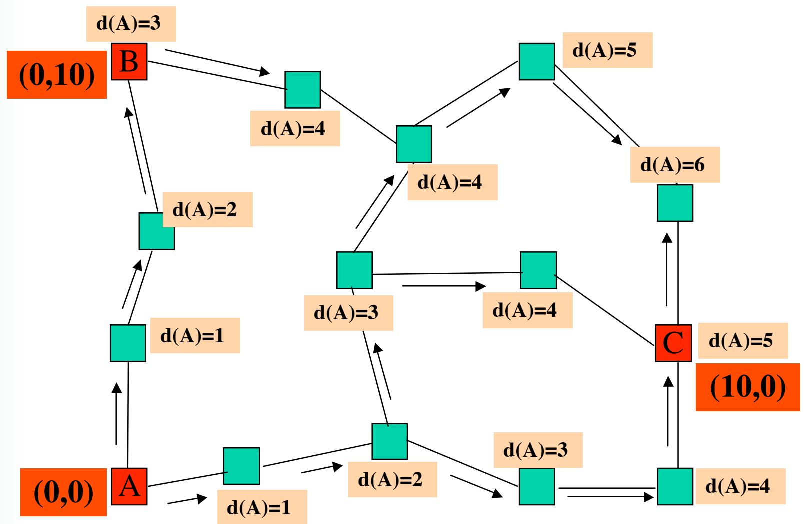

Example

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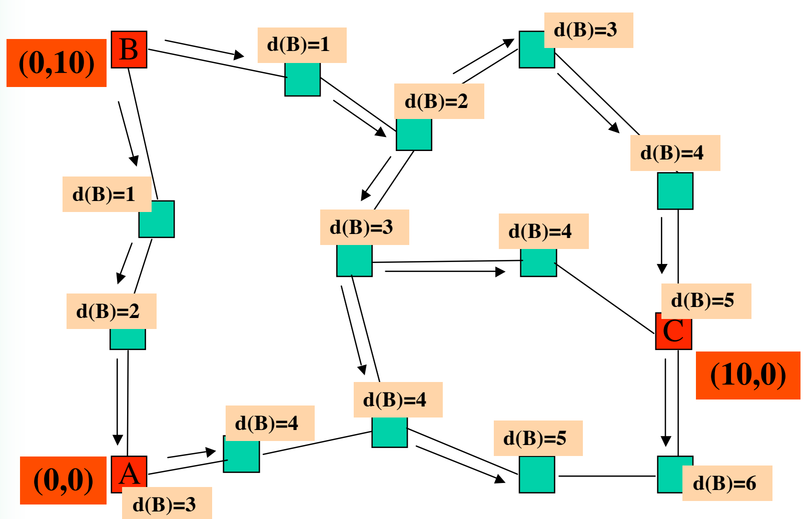

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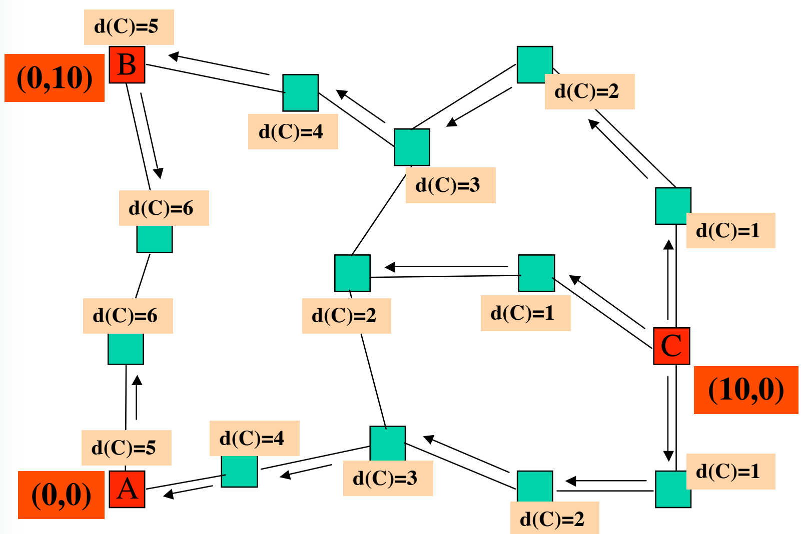
Example



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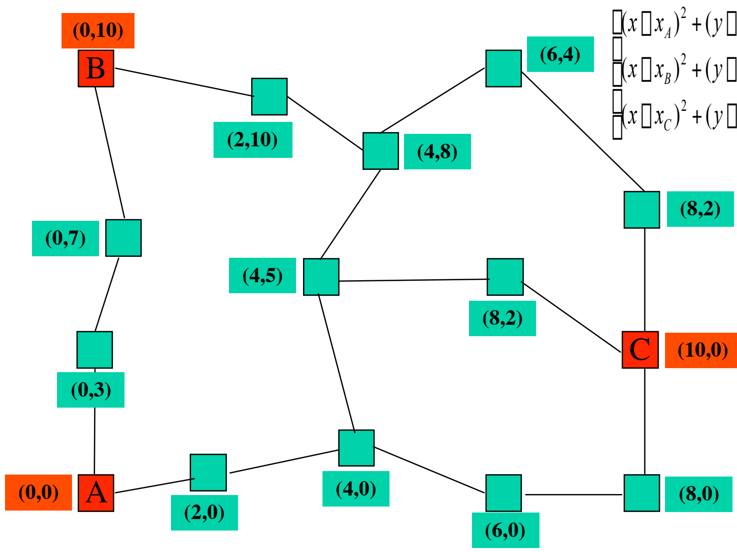
Example



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Routing Issues…

- Once devices know their location…
- How can you route data across the network from a device to another device at a specific location?
  - E.g., in the wall of invisibility, from an IN device to the OUT devices on the opposite side of the wall?

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Location-Dependent Routing

- Take advantage of devices' location knowledge to route information
  - Information sent to a particular location, rather than to a particular device
- Each node knows its and one-hop neighbors' coordinates in a frame common to all the network
  - Physical space
    - the case of the wall of invisibility
  - Virtual Space:
    - The concept of overlay networks in the Internet
- If the space is a continuum
  - The message is propagated in the network on the basis of simple Euclidean considerations
  - To devices closer and closer to the goal

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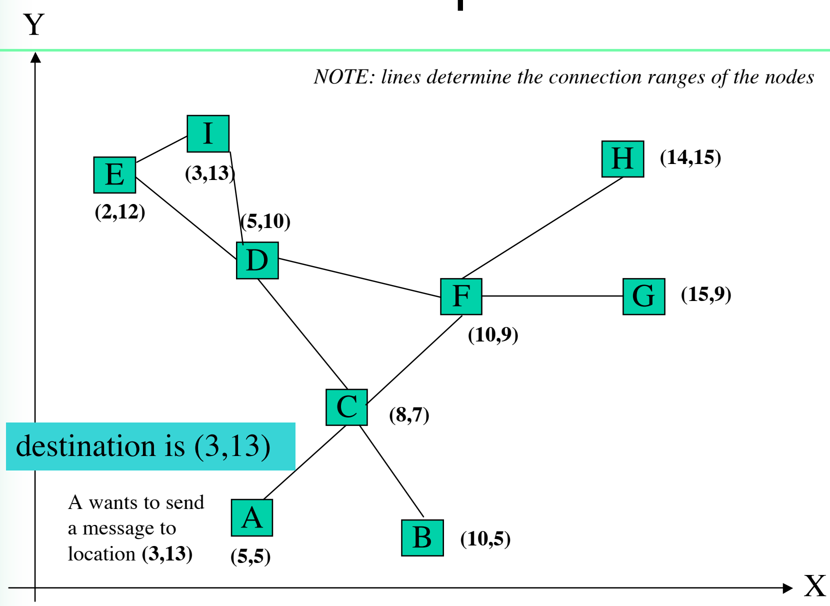
Example



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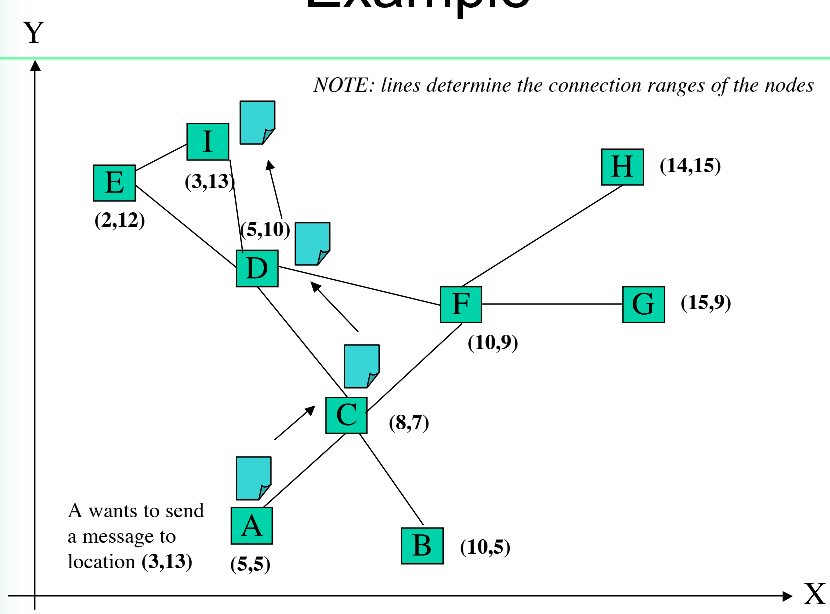
Example



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Advantages of Location-based Routing

- The message is directed “closer” to the right location
  - Reaching the “closest” locations the goal
  - Suits uncertainties
  - Suite network dynamics (nodes can move or die)
- In the wall of invisibility:
  - Do not matter if there is not a sensor at the exact location
- In the Internet
  - Different approaches proposed for virtual overlay networks based on virtual physical spaces (e.g., Pastry defines a virtual 1-D, CAN defined a generic N-D space)
  - If similar services are mapped on close portion of the virtual spaces
    - One do not need to know the IP of a server nor it requires that a specific server is on
    - Just need to reach the zone close to that service….

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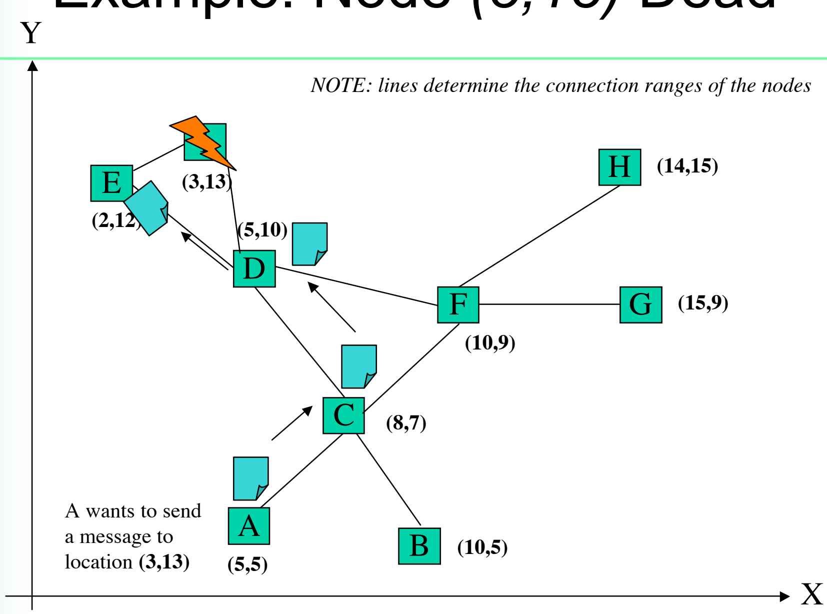
Example: Node *(3,13)* Dead



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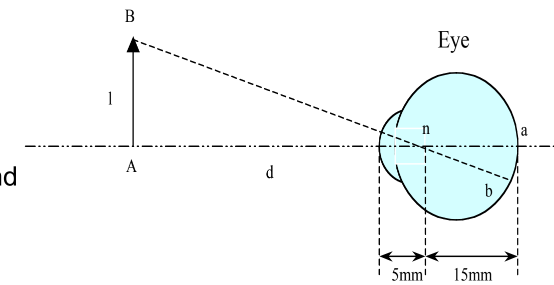
Back to the Invisible Wall: Hardware Issues and Apps

- How many devices and how small?
  - The Listing-Donders model of the human eye
  - to rend invisible a *1m²* wall from a distance of *10m*, you'd need each device to be approx. *8.4mm²* wide and capable of *286 kbits/sec* wireless bandwidth (30 frames/sec)
  - No problems! (see, e.g., Smart Dusts)
- Applications
  - Paintable TVs and monitors



The Clock of Invisibility: Structure of the Presentation

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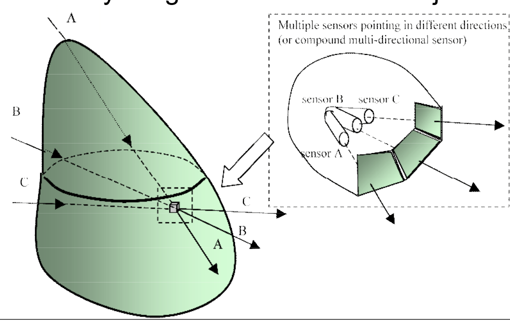
The Invisible Object

- You no longer separate the object into IN and OUT sides
  - Both IN and OUT devices densely packed in the surface (or packed in a single compound device)
  - Painted with a random orientation, so as to probabilistically have sensor in "all" directions
  - Possibility to reproduce "all" ray of lights incident on the object
    - For any point of the surface
    - For any direction of observation



Software Issues: Self-Localization

- Route light information from one device to the co-aligned device on the other side of the object….
- More than 2-D self-localization on the surface:
  - Each device must know its **coordinates w.r.t. to a 3D reference frame** attached to the object
  - And its **orientation**
  - So as to determine which ray of light it blocks
  - And to determine its "mate", i.e., the device to which to send the light information to reproduce
- And this has to be done:
  - Without any a priori assumption or global knowledge about the object shape
  - Without any a priori global knowledge of devices' orientation

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Evaluating Surface Coordinates: 3D Triangulation

- Potentially possible to extend triangulation mechanism
  - By using 4 non-aligned beacons
  - And by triangulating over a 3D space
- But this cannot be generally applied!
- **Problems**
  - For short range communications, the process must be iterative
  - Devices, in turn, must act as beacons to have the evaluation of coordinates propagate
  - However, in the case of nearly flat portions of the surface
    - One cannot find 4 non-aligned devices to act as beacons!!!
    - This can produce errors!

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Evaluating Surface Coordinates: Curvature

- A completely different approach:
  - 2D triangulation **AND**
  - Curvature estimation
- In particular
  - Devices, other than reciprocal distances, evaluate the local curvature of the surface
  - this enable to reconstruct iteratively the global shape of the surface and accordingly,
  - Determine the 3D position of a device: ***(x,y,z)***
- Problem: How can a device "painted" on a surface determine the surface local curvature?
  - It cannot rely on any external 'view' of the surface to see if the surface locally bends…

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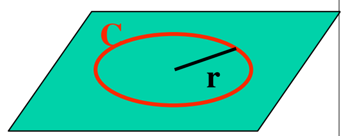
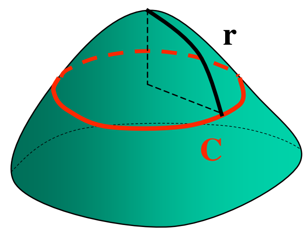
Theoretical Solution

- Manifold geometry suggest how to estimate curvature even without an external view.
- The ratio of the the circumference to the circle's radius changes with the curvature…..
- In a flat surface: **C/r = 2π**
- In a curved surface:
  C/r decrease as curvature increase
- Thus, each device in the network has to:
  1. Evaluate the circumference of a circle centered in the device (**C**)
  2. Evaluate the radius of the circle (**r**)
  3. Compute **C/r** see from this how far **C/r** is from **2π** to evaluate the curvature

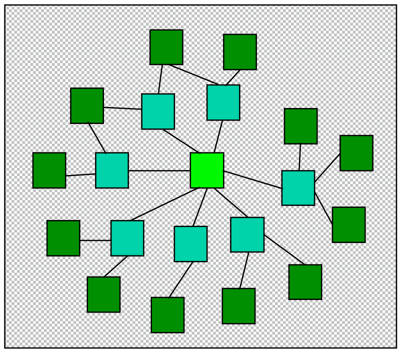




Implementation

- If the network is ***dense*** and with a ***uniform density*** **C** and **r** can be evaluated counting the number of devices on the circle and on the radius…
- Each device send a hop-count broad cast message that spread until an intended fixed number of hop **r**.
- Devices receiving the hop-count message with hop-count = **r** send a message back to the original device.
  - **N.B.** These device are the ones on a circle of radius **r** centered on the original device.
- The device counting the number of replies can evaluate **C**

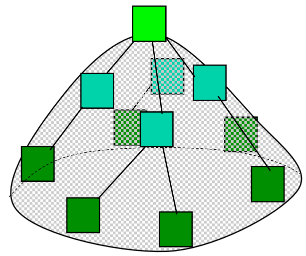
Example



r = 2 C = 12

C/r = 6 ~ 2π

Almost Flat



r = 2 C = 6

C/r = 6 ~ π

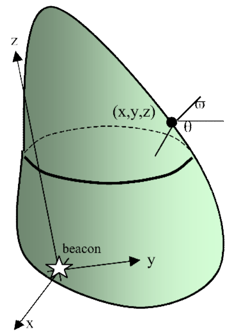
Curved

More on Curvature Estimation

- Several other intrinsic curvature measures…
  - E.g. Area / radius.
  - Performance measures needed on real world systems → still missing.
- Other potential applications
  - Using sprayed sensor networks
  - Monitoring stresses and deformations in artifacts (e.g., skyscrapers, bridges, airplane wings)
  - Monitoring evolution of "turbulences" in fluids
- In general, manifold geometry can provide useful algorithm to dynamic networks and to to smart and self-assembly artifacts

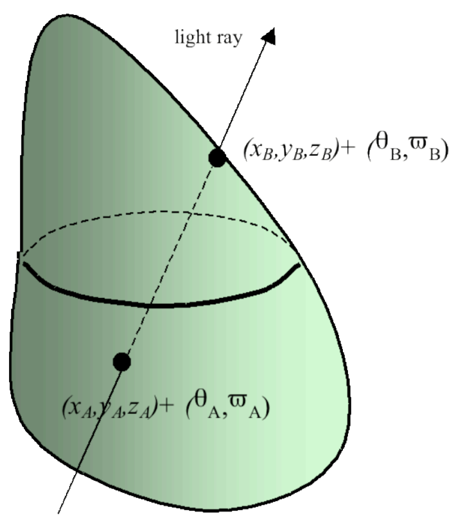
Determining Devices Orientation

- Devices need to know the direction to which they are directed in a common frame.
  - Remember they have been "sprayed" on the surface with a random orientation
- Approaches
  - Beacons also act as orientation reference
  - Estimate relative orientation between two devices
    - Ray-based communication (Infra-Red)
    - See the "Cricket Compass" approach
  - From beacons, propagate and adjust this relative measure by taking into account curvature information



Self-localization: Eventually…

- Each device on the surface **KNOWS**:
  - Its coordinates **(x,y,z)**
  - Its orientation **(□,□)**
- And accordingly:
  - The coefficients of the ray of light it block or it has to reproduce



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Software Issues: Routing on the Invisible Object

- This is a bit more challenging than in the case of the invisible wall…
- Problems:
  - Even if a device knows
    - WHICH ray of light it blocks
  - It does not know
    - WHERE the “mate” devices that should reproduce it is on the object and in which direction a message should go to reach it
    - This may strongly depends on the surface on the object
    - There is no way to be sure that a direction is correct
  - We cannot certainly think at “flooding” messages over all the network….

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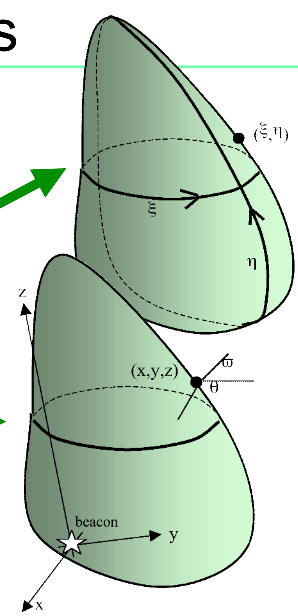
Intrinsic Vs. Extrinsic Coordinates

- Terms coming from differential geometry
- Useful to understand the routing problem
- **Intrinsic coordinates**: coordinates ON the surface ***(_,_)***
- **Extrinsic coordinates**: coordinates with reference to an external fixed frame ***(x,y,z)*** – better, taking into account orientation too ***(x,y,z)+(□,□)***



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Routing with Extrinsic and Intrinsic Coordinates

- **Extrinsic coordinates**
  - **PRO:** Code all the information related to the actual shape of the surface (and so of the ray of light associated with a device).
  - **CONS:** It is difficult to route information toward a specific point without global knowledge of the surface → cannot be used for the invisible object
- **Intrinsic coordinates**
  - **PRO:** allows to route information by using simple Euclidean considerations (as the location-based routing in the invisible wall)
  - **CONS:** Gives no information to the actual shape of the surface (and so, gives no information on where to find the needed device)
  - **PS** intrinsic coordinates self-localized easily (2D coordinates!!!)

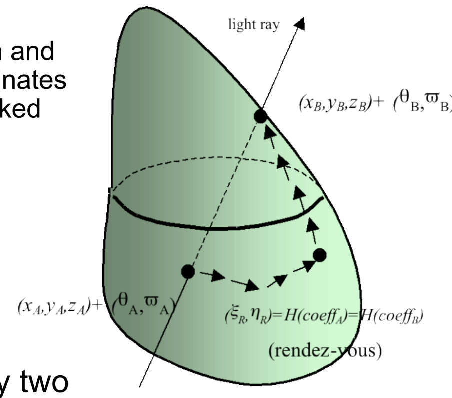
Routing in the Invisible Object: a Solution

- Exploit the intrinsic coordinates by
  - Using a function ***H*** (*hash*) that maps extrinsic coordinates into intrinsic ones

    *(_,_) = H(**x,y,z,□,□**)*
  - Route a message towards the derived intrinsic coordinates (location-based routing, as already described)
- The derived intrinsic coordinates determines a devices that act as a "***rendez-vous***" point
  - A sender send a message on the hashed coordinates of the receiver
  - The receiver go looking for messages on its hashed coordinates

Rendez-Vous Communication

- When a sensor block a ray of light
  - It code the color information and send it to the hashed coordinates of the ray of light it has blocked
- When an emitter has to reproduce a ray of light
  - It goes looking for color information at its hashed coordinates
  - Once obtained, it route the information backwards
- In a convex object the only two devices having that same coefficients are the communicating partners.



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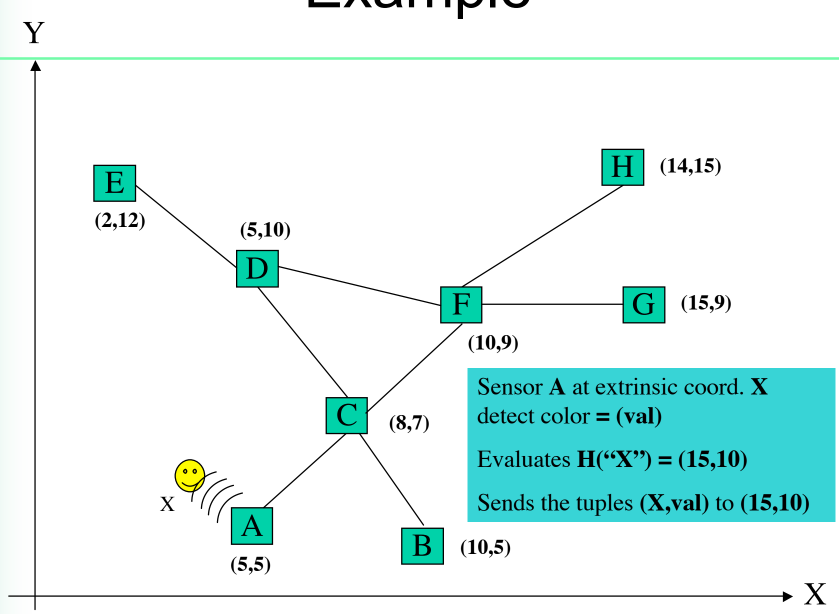
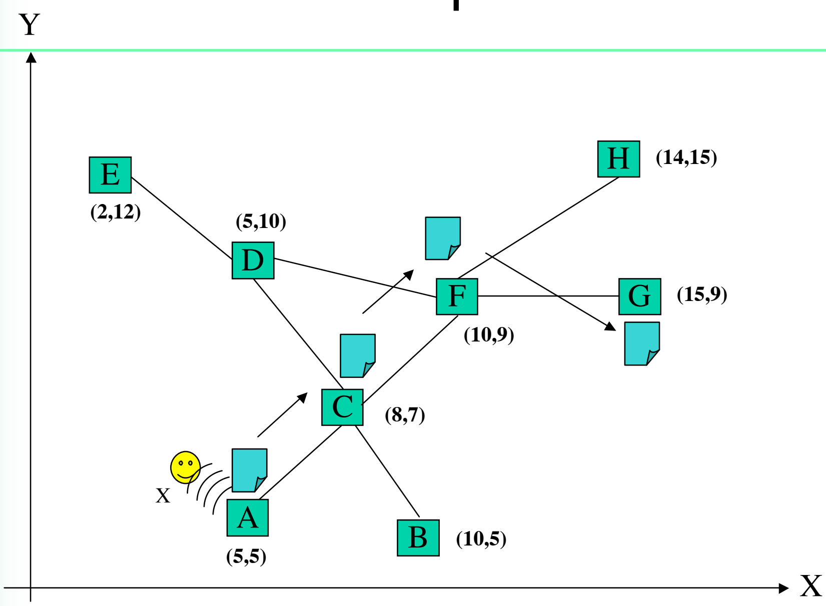
Example



Example

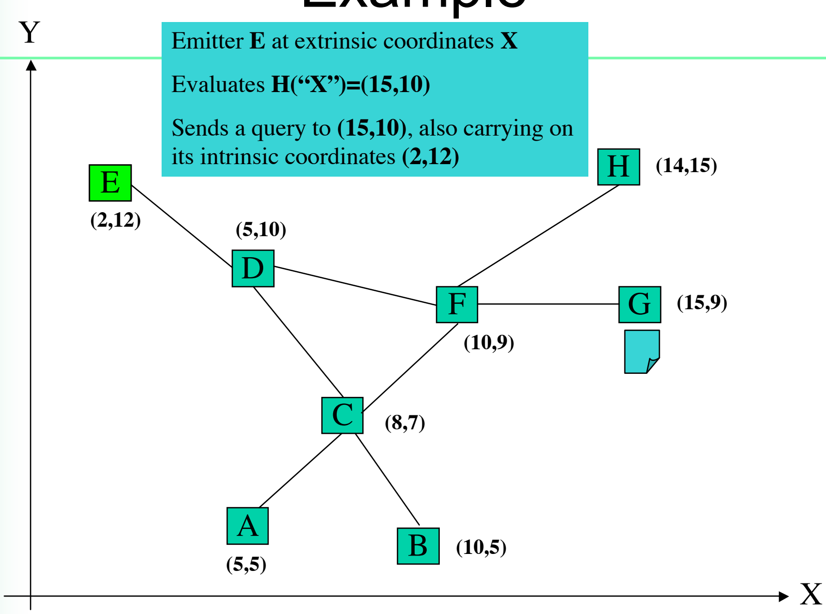


Example

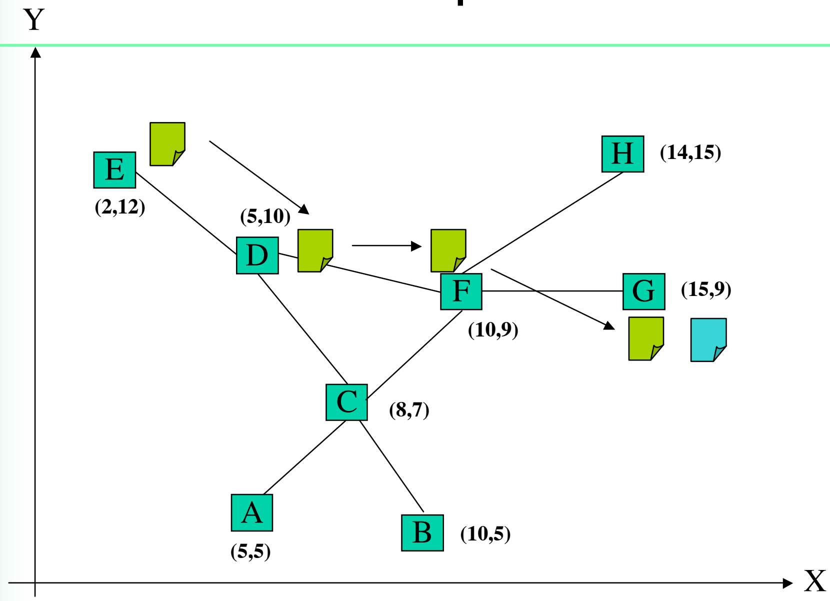
Emitter **E** at extrinsic coordinates **X**

Evaluates **H(“X”)=(15,10)**

Sends a query to **(15,10)**, also carrying on its intrinsic coordinates **(2,12)**



Example



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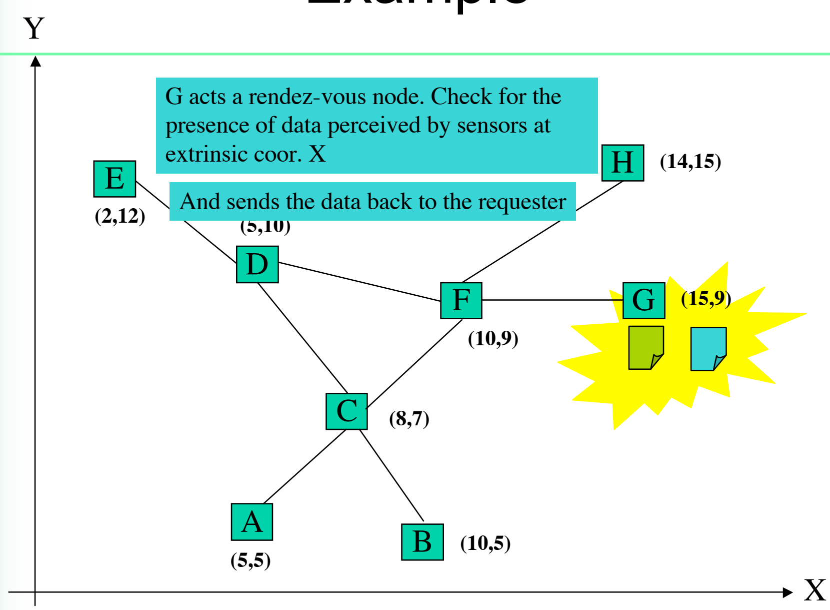
Example



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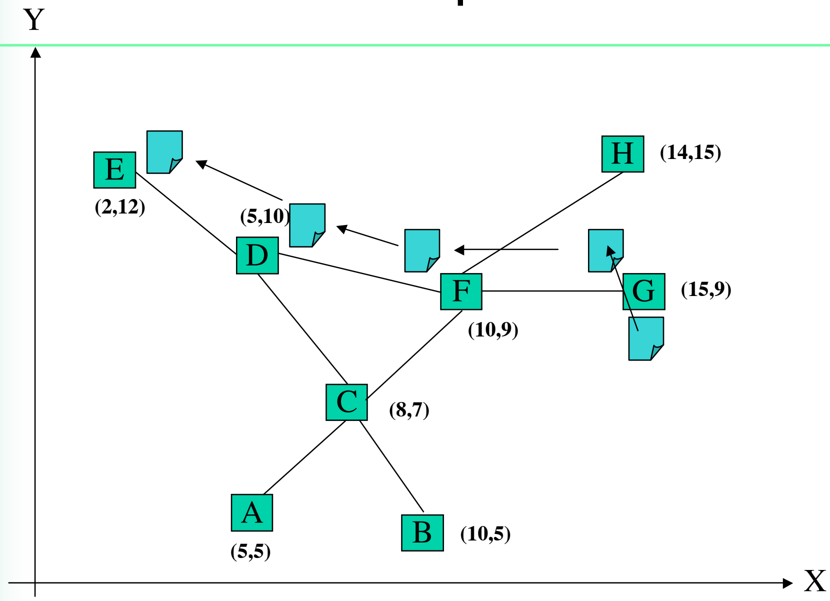
Example



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Content-based Routing on the Internet

- CAN (Berkeley), Pastry (MS Research), Chord (MIT)
- All relying on the same concept of “overlay network”
  - A virtual network structure built over the physical Internet
  - Virtually Connecting nodes according to specific rules
  - The overlay network defines a sort of virtual space, and nodes are connected if adjacent in the space
  - So as that it is possible to navigate in this network
- Example:
  - Pastry & Chord: nodes logically connected in a ring → a 1D logical space
  - CAN: nodes virtually associated to a region of n-D space, each nodes virtually occupying such region and connected to nodes on adjacent regions

Hashing for Content-based Routing on the Internet

- Peer share an hash function ***H***
  - mapping strings (or, in general, some sort of “content”) into virtual space coordinates
  - Data (or messages) with a specific content is sent to the the position ***H(content)*** in the virtual spaces
  - Requests for data with a specific content are looked for at the position ***H(content)***
- Example: mp3 file exchange
  - When a peer connect, it is assigned a position in the overlay network and a set of neighbors→ some sort of “space” balancing is enforced
  - Should some nodes die or disappear, the structure is automatically updated
    - nodes recognize a neighbor is dead and re-distributed in the virtual space, to reoccupy the portion of the space left free
  - A peer having the song *“Hey Jude”* sends a tuple *(“Hey Jude”,IP)* to peer located at *H(“Hey Jude”)*
  - A peer looking for song *“Hey Jude”* queries device at *H(“Hey Jude”)* finds *(“Hey Jude”,IP)* and starts downloading.

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Back to the Invisible Object: Hardware Issues and Apps

- To rend invisible a *1m*-diameter sphere from a distance of *10m*, you’d need
  - ***372,000* compound objects**. Each
  - composed by ***186,000* mono-directional devices**
  - each ***5_m*5_m*** wide
  - with a ***3.4 Mbits/sec*** communication channel.
- Impossible???? Let’s say challenging…
  - Texas Instruments, produced micro-displays made up of electro-statically actuated mirrors of a few m^2
  - Philips Research Laboratories, showing the possibility of growing micro-scale LCD cells on any type of surface
  - Terahertz-band wireless communications potentially possible on silicon
- Applications…limited by fantasy only…
  - Invisible cars, tanks, painted windows, improve rear visibility in trucks, immersive virtual reality environments…

The Clock of Invisibility: Structure of the Presentation

- The Invisible Wall
  - Provide invisibility for a regular shaped rigid object, from a single fixed point of observation
  - Key issues: 2-D localization, location-based routing
- The Invisible Object
  - Provide invisibility for a rigid object of whatever shape and from whatever point of observation
  - Key issues: 3-D self-localization, content-based routing
- The Cloak of Invisibility
  - Provide invisibility for a flexible fabric from whatever point of observation
  - Key issues: Dynamic re-localization, Routing on mobile ad-hoc networks

The Cloak of Invisibility: Software Issues

- Remove rigidity constrain
  - Deploy the network of devices on a flexible fabric, re-shaping due to unpredictable dynamics (e.g. wind and wearer's movements)
- Problems
  - Extrinsic coordinates of devices changes continuously → **dynamic re-localization**
  - Communication partners (IN and OUT pairs) change continuously, and so the route paths
- Similar challenges found in MANET
  - Well, the cloak is a MANET indeed….

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Dynamic Re-localization

- Re-compute the self-localization process periodically
  - it would make it possible to leave the location-based routing protocol unchanged
  - Feasible depending on involved dynamics
    - In the cloak, it appears unfeasible (30 frames/sec)
    - Also very expensive
- Base the coordinate system on a fixed point for geometrical references
  - evaluate coordinates as displacements to the fixed ones
  - In the cloak, these could be the belt or a necklace
  - Forces load unbalanced in the cloak

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Routing on Mobile ad-Hoc Networks

- How are this problems faced on MANETs? (Mobile ad-hoc Networks)
  - Clouds of computer-based nodes (e.g., PDAs)
    - continuously changing their position (e.g., because carried on by moving persons)
    - With short range connections
  - And where messages must be sent from a node of the network to another nodes
    - possibly requiring multi-hopping and intermediate nodes retransmissions
- A number of routing protocols are getting proposed
  - Table-driven, On-demand, adaptive location dependent protocols…
  - The most effective ones are based on a known social phenomena…

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The Gossip Phenomena

- Gossiping is a very effective phenomena
  – Stupid and useless information travel social networks in a very fast way
- How does it work?
  – Alice knows something interesting
  – Tell it to a number of acquaintance
  – And so on, recursively
- The source of a gossip can be backtraced
  – Hey, who told you that?
  – Alice, who was said by Bob, who was said by Charles….
  – And so on recursively, backward to the source

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Gossip Algorithms

- Based on a simple yet effective idea
  – Let propagate in the network some sort of **random** "pheromone" path, leading backwards to a specific node or to a specific data
  – Let a sender (or some node in need of specific data) start randomly search in the network one of these paths
  – As soon as one is found, the path is followed backward
- It's a probabilistic approach
  – The more the paths and the more extended is the search, the higher the probability to find a path soon
  – However, experimental results shows it works extraordinarily well
- Possible Applications:
  – Sensor networks (and the cloak of invisibility)
  – Publish-Subscribe and P2P computing on the Internet

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Pros & Cons

- Pros
  - Never Flood
  - Work incredibly well, against the apparently unreasonable starting assumptions
  - Everything is dynamic, so that mobility of nodes is tolerated without any pain
- Cons
  - Not certain performances
  - Strongly depends on the structural properties of networks

Back to the Invisible Cloak Hardware Issues and Apps

- Size of devices does not change, however:
  - **CONS** More bandwidth required to deal with coordinates update and more complicated routing
  - **PROS** Cloak movement or human body thermal energy can be used to recharge cloak's devices
- How much for an Invisible Cloak ?!
  - The Institute for Defense Analysis has predicted that MEMS cost in the near future will reach **1 Euro** each.
  - A cloak of invisibility of *3m*^{2} would require approximately *372,000* compound (multidirectional) devices to be invisible at a *10m* distance, implying an overall cost below a **half-million Euros/Dollars**.
- Applications:
  - Invisible suits, fashion (e.g., invisible frames on T-shirts), monitoring of complex dynamic internals, body monitoring

Emergent Behaviors

- Self-organization vs. emergent organization
- Compare again with complex dynamical systems
  - The system evolves according to specific (physical) laws
  - Towards an "**attractor**"
    - Specific final state or a dynamic trajectory state
- In the case of a single attractor
  - The system always converges toward the same configuration
  - Complex but predictable behavior
    - We may not understand at the micro-level functioning
    - Final attractor may be per se complex
    - Re-stabilization in the case of changes
  - But we can engineer the systems
    - We know where it will head to
    - E.g., self localization
  - ***There is nothing that "unexpectedly" emerges***

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Emergence

- In the case of multiple attractors
  - The system may evolve toward a multiplicity of configurations
  - We may not know in advance which one to be reached
  - We may not even know all of the potential configurations
- Apparently strange "emergent" behaviors
  - Usually, a single well-known attractor is reached
  - Sometimes, a different one is reached
  - As known, it may depends on initial configurations ("the butterfly effect")
  - But this is not necessarily the case in distributed computing systems…
- Also, in the case of dynamic perturbations
  - The system can moving from one attractor to another….
  - Continuously changing dynamic trajectories

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Emergence != Disorder

- Emergent behaviors does not always mean "Chaos"
  - That's what we have learnt to think, but
  - In many real world systems there is an intrinsic tendency to order as an emergent, unpredictable behavior
  - Although "order" may not be immediately recognizable
- Complex networks
  - Apparently random, indeed structurally regular (small world and scale free)
- Spatial patterns
  - Solitons, granular media, population dynamics…
- Synchronization
  - Clapping, walking, bees ritual dances
- Can we exploit this in pervasive computing and in "spray computers" ???
  - Very very likely….

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Using Emergence ?

- Emergent behaviors may be dangerous
  - I did not want my system to behave like that!!!
  - e.g., global load unbalances in a network
- But may be useful
  - I could have never obtained such a global behavior by direct engineering !!!!
  - e.g., a robust and stable global coordination pattern
- Let's see what happens in real system…
  - The case of complex networks…

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Complex Networks

- Complex web-like network structures are pervasive
  - **Graphs of relations between nodes**
  - describe a wide variety of systems
  - of high technological and social importance
- Examples
  - Human sexual relations are networks of contacts between persons
  - The cell is best described as complex network of chemical connected by chemical reaction
  - The Web is a complex network of HTML pages connected by hyperlinks
  - Scientific citation indexes define networks of citations between papers
  - Etc. etc.

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Why Complex Networks are Important ?

- Studying the behavior of systems consisting of complex networks is a tremendously challenging task
  - not a problem of constituents (kinds or number)
  - but a problem of network structure and interaction patterns
- Complex structures and interaction patterns (i.e. network structure) are at the basis of:
  - Routing performances in the comm. networks
  - Document retrieval in the WWW
  - Earthquakes happenings
  - Spread of infectious diseases
  - **Activities in spray computer networks**

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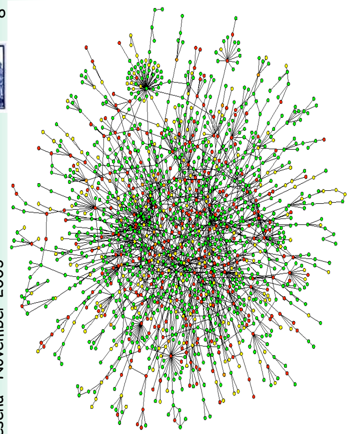
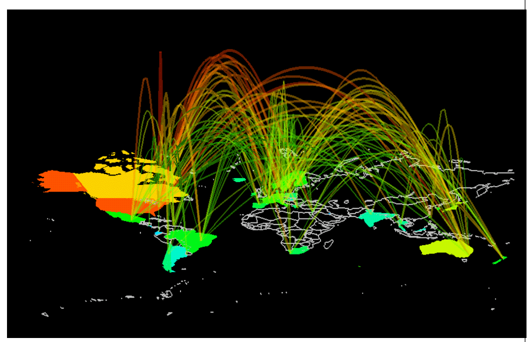
Isn't complex just random ?





http://www.nd.edu/~networks/gallery.htm

Proteins interaction network

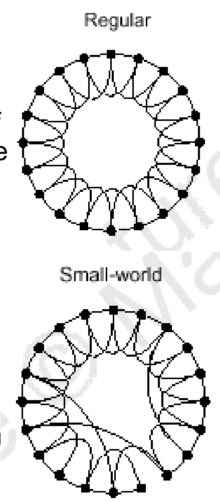
Internet traffic network

Complex Networks Properties

- All complex networks, despite dramatically different at the micro-level, are very similar in terms of
  - Macro-level structure
  - Mechanisms of formation and interactions patterns
- Three concepts occupy a prominent place in contemporary thinking about complex networks
  - **Small World**
  - **Clustering**
  - **Power law degree distribution (scale free)**
- Strictly inter-related with each other..

Small World

- Despite their very large size, most networks have a relatively short path between any two nodes.
  – Milgram (1967) experiment: “six degrees of separation” between any two persons in the USA
  – Average path length of the whole WWW is 16.
  – This is due to the fact that:
  – Even if most connections between nodes are local and sometimes very regular (e.g., we know everybody in the neighborhood)
  – There are long-range connections between nodes (e.g., we know someone over-ocean
- This implies *(Watts and Strogatz, 1998)*
  – A dramatic shortening of average path between nodes



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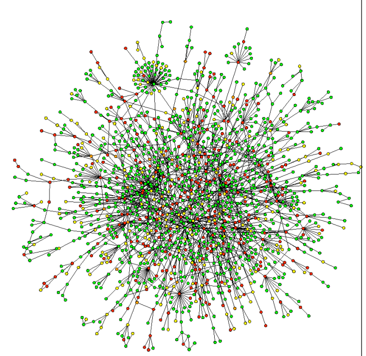
Clustering

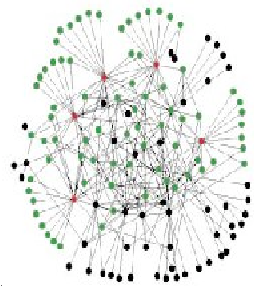
- A common property of complex networks is that “cliques” of nodes form
  – Cluster of highly connected nodes
  – Loosely connected with other clusters
  – e.g., most of our friends always meet with only each other, and a few of them meet other persons around…
  – e.g., most of us navigate 90% of the time in a few Web sites, and rarely visit new sites
- This appears to be an inherent tendency in networks



Power Law Networks

- Forget Gauss and the central limit theorem

$$P(k) = k^{-\gamma}$$



- Typical of social networks
  - A large number with few connections
    - E.g., those not-so-friendly colleagues, our Web page ;-((
  - A few (but not irrelevant) number of highly connected nodes → "hubs"
    - E.g, YAHOO!, our friends knowing everybody….
- Power law (i.e. heavy tails) are Scale free (structure preserved despite size)!

Implications of Emergence in Complex Networks

- Once deployed, most types of network systems will inevitably define complex networks…
  - Small-world, clustered, scale free
  - Also in the case of "spray computers" – provided long-range interactions are somehow enabled
  - After all, the Internet is a big "spray computers"
- So what?
  - Even without explicit engineering we will build complex structured networks…
  - The kind of networks exploited by nature in a lot of fields…
  - And the key point is that nature is a good engineer (builds **robust** and **flexible** systems…)

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Applications of Emergence in Complex Networks

- Research in this topics is still in its infancy…
  - Most of the studies have a *scientific* rather than *engineering* purpose
  - They try to understand properties of these networks and define taxonomies
    - Are we missing some key ingredient?
    - Could we do better than nature?
    - How can we use such type of emergence?
- Though, there are already some **concrete application** of these concepts:
  - ***Gossiping in ad-hoc networks***

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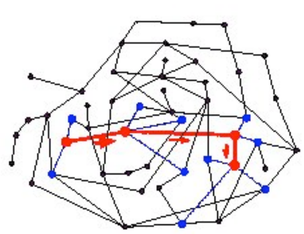
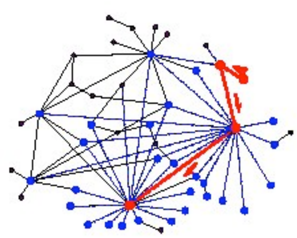
Gossiping in Complex Networks

- Network structure has a strong impact on the reached nodes by a random walk….
- Complex network structures enhance performances of gossip routing algorithms…
  - **Small-world** → it is easy to reach far nodes
  - **Clustering** → related nodes are greatly connected
  - **Power-Law** → queries and data are more likely to encounter



Random Network



Power Law Network

BLUE node reached in one-hop neighborhood, by a **RED** random walk

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Spatial Networks

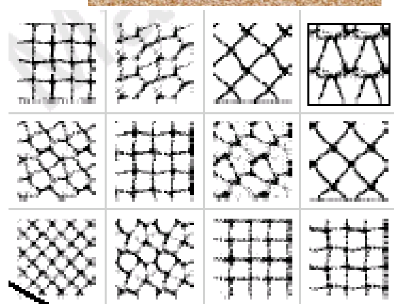
- Network of "components" that are
  - Made up of autonomous (or weakly correlated) components
  - spatially distributed in an environment
  - Perturbed in their activity by such environment
  - Interacting with each other (directly or indirectly) in a limited spatial range
  - Sometimes exhibiting non-local interactions
- These include a large number of physical systems
  - Physics: solitons, granular media
  - Biology: populations, ants, etc.
- And also "spray computers"
  - Autonomous computer-based components diffused in an environment and interacting accordingly to their short-range wireless connections

What does it Happen There ?

- There are surprisingly similarities in the dynamic evolution of all these kinds of systems
  - Starting from any apparently "random state"
    - Random positions
    - Random local states and activities of components
  - Mostly evolving based on local interactions
    - Local small movements
    - Local competitions
  - And providing that external perturbations keep the system out of equilibrium
- The whole system tends globally coordinate to exhibit long-range – often very regular – spatial patterns of
  - Activity (global coordination of activity)
  - Distribution (global mobility patterns or globally regular aggregations)

The Case of Granular Media

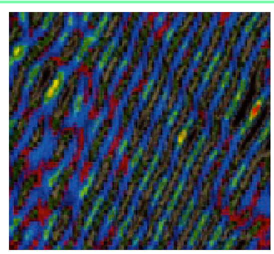
- Under specific perturbations regimes
  - E.g., wind, vibration, injection of new material
- Granular media may exhibit surprisingly regular pattern
  - Global coordination patterns
  - Without control of micro-components
  - Reproducible
- Also sand dunes and rock in Alps and Alaska

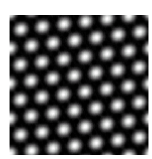


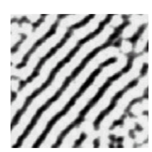
From "Nature", 2001

The Case of Solitons

- Autonomous photons
  - Trapped in their own electromagnetic field
  - With noise frequency (randomness)
- When interacting together
  - Crossing with each other and making their electromagnetic fields interact
- Large-scale regular visual patterns emerge







From "Nature", 2001

Other interesting cases…
(there's no time for everything..)

- Ants and Termites
  - Shortest path routing
  - Sorting, task differentiation
  - Distributed building of complex nests
- Flocks of birds and fishes
  - P2P Group formation
  - Group-based chameleon camouflage
- Humans
  - the Mexican wave
  - Growing of urban centers

Emergence of Coordination in Computational Systems

- Can similar spatial patterns emerge in distributed computing systems?
  - Yes, since they share similar characteristics with the previously analyzed systems
    - Spatial distribution
    - Autonomy of decentralized activities
    - (mostly) local interactions
    - Perturbations (autonomous behavior and situatedness)
  - This would imply the emergence of **global scale coordination** of the system!
- The example of
  - **Cellular automata (CA)**
  - As a minimal spray computer system

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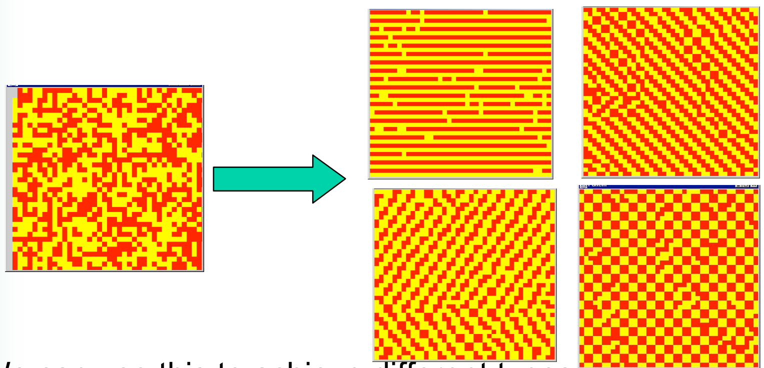
Emergent Behaviors in CA

Global scale behaviors emerge from even simple CA

Similar to the ones observed in real world systems



We can use this to achieve different types of global spatial coordination in spray computer systems….

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Open Research Issues

- Complex Networks vs. Spatial Networks
  – Do they really differ?
- Programming Languages & Middleware
  – Which models to program self-organizing pervasive applications
  – Which middleware can support such models
- Distributed Intelligence and multiagent systems
  – Distributed introspection → what's happening
  – Distributed self-control → let's re-organize ourselves

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