Distributed Coordination of a Set of Autonomous Mobile Robots: The Unlimited Visibility Setting

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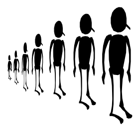
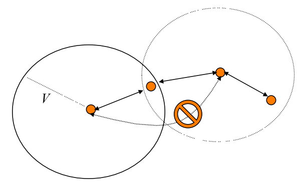
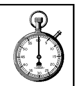


Radius of Visibility: Limited / Unlimited



Timing Models



ASYNC/CORDA - *Fully asynchronous* [Flocchini et. Al, 1999]

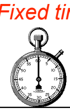
Arbitrary & varying operation rates and delays

SSYNC/SYM - *Semi-synchronous* [Suzuki +Yamashita, 1996]

Fixed time cycles, but robots may be active / inactive

FSYNC/SYM - *Fully synchronous* [Suzuki +Yamashita, 1996]

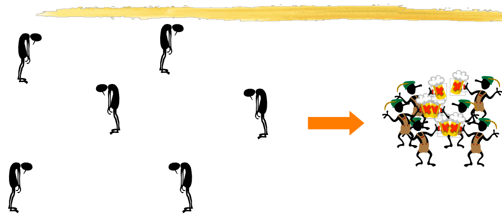
Fixed time cycles, all robots active in every cycle



Problem 1: Gathering,

(Aggregation, rendez-vous, homing)

Gathering - Unlimited Visibility



Initially the robots are in arbitrary distinct positions.

In finite time, they **gather** in the same place.

Motivations

*A conference is a **gathering** of important people who singly can do nothing, but together can decide that nothing can be done*

Fred Allen (1894-1956)

Gathering

- In spite of its apparent simplicity, this problem has been tackled in several studies

Gathering
Unlimited Visibility - SSYNC

Ando, Oasa, Suzuki, Yamashita
Siam Journal Of Computing, 1999

- **Istantaneous activities**
- **n=2, the problem is unsolvable**

Gathering, n=2
Unlimited Visibility - SSYNC

In fact, since the robots have no dimension…

…and cannot bump...

…moving them towards each other is not useful…

…but it works if they can *bump!*

Gathering
Unlimited Visibility - SSYNC

Ando, Oasa, Suzuki, Yamashita
Siam Journal Of Computing, 1999

- **Istantaneous activities**
- **n=2, the problem is unsolvable**
- **n>2, they provide an oblivious algorithm that let the robots gather in finite time**

Gathering
Unlimited Visibility - SSYNC

- MAIN IDEA: Starting from distinct initial positions, we move the robots in such a way that eventually there will be exactly one position that two or more robots occupy
- Each time a robots becomes active, it recognizes the configuration of the robots (7 possible configurations)
- It moves accordingly

Gathering
Unlimited Visibility - SSYNC

Few examples:

- Let C be the smallest enclosing circle of the observed configuration
- If n > 3, and there is exactly one robot r inside C
  - r moves towards one of the robots on the rim of C; the others do not move
- If n > 3, and there are more than two robots inside C
  - The robots inside C move towards the center of C, while the other do not move (the center of C does not change)

Gathering
Unlimited Visibility - SSYNC

- <u>If n > 3, and all robots are on the rim of C</u>
  - All robots move towards the center of C

- In the last case, at the next time instant
  - Either some robots are inside C and some on the rim of C
    - One of the previous cases applies
  - Or all robots are again on the rim of C
    - This same case applies again

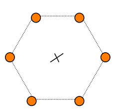
Gathering, ASYNC

- In ASYNC, several factors render this problem difficult to solve

  - Major problems arise from symmetric configurations....

Difficulties

If at the beginning....



Difficulties

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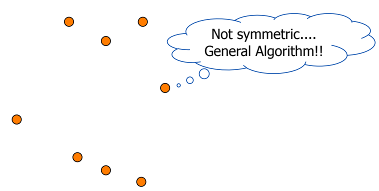
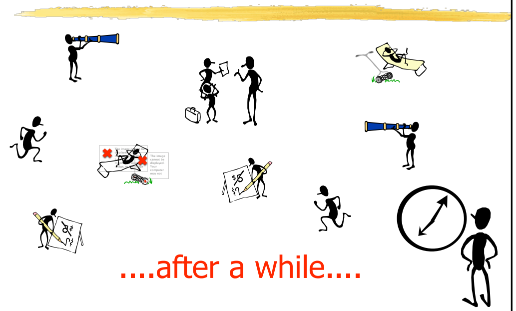
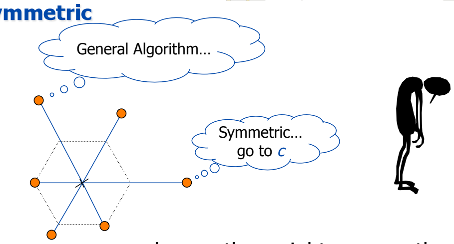


Difficulties



Difficulties

Symmetric



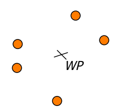
....hence, they might never gather!!!!

Gathering—easy solution

Easy Solution: Weber Point (Weiszfeld, '36)!

Given $r_1,\ldots,r_n$: $WP = \arg\min_{p \in \Re^2} \sum_i \mathrm{dist}(p, r_i)$

1. It is unique (Weiszfeld, '36)



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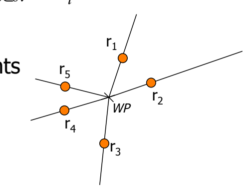
2. WP is Weber Point of points on $[r_i, WP]$ (Weiszfeld, '36)



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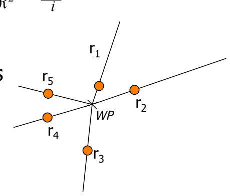

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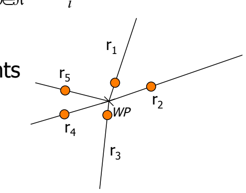

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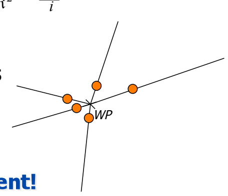

WP Invariant Under Movement!

Gathering—easy solution

Easy Solution: Weber Point (Weiszfeld, '36)!

Algorithm:

1. Compute WP
2. Move Towards WP

Unfortunately, WP is not computable!

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Gathering
(Unlimited Visibility, no agreement)

n=2: Unsolvable (by Suzuki *et al.*),
unless they can *bump into each other*!

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Gathering
(Unlimited Visibility, no agreement)

n=2: Unsolvable (by Suzuki *et al.*),
unless they can *bump into each other*!

n=3,4: Always solvable!

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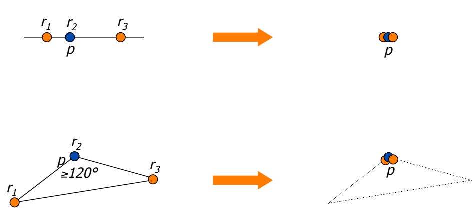
Gathering, *n=3*
(Unlimited Visibility, no agreement)



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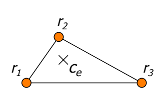
Gathering, *n=3*
(Unlimited Visibility, no agreement)



Properties of c_e:

c_e=center of equiangularity

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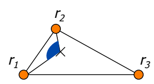
Gathering, *n=3*
(Unlimited Visibility, no agreement)



c_e=center of equiangularity

Properties of c_e:

- $r_1\widehat{c_e}r_2$

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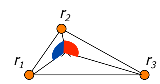
Gathering, *n=3*
(Unlimited Visibility, no agreement)



c_e=center of equiangularity

Properties of c_e:

- $r_1\widehat{c_e}r_2 = r_2\widehat{c_e}r_3$

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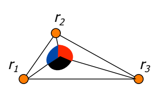
Gathering, *n=3*
(Unlimited Visibility, no agreement)



c_e=center of equiangularity

Properties of c_e:

- $r_1\widehat{c_e}r_2 = r_2\widehat{c_e}r_3 = r_3\widehat{c_e}r_1$

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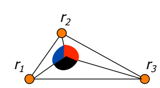
Gathering, *n=3*
(Unlimited Visibility, no agreement)



c_e=center of equiangularity

Properties of c_e:

- $r_1\widehat{c_e}r_2 = r_2\widehat{c_e}r_3 = r_3\widehat{c_e}r_1$
- Invariant under movement

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Gathering, *n=3*
(Unlimited Visibility, no agreement)

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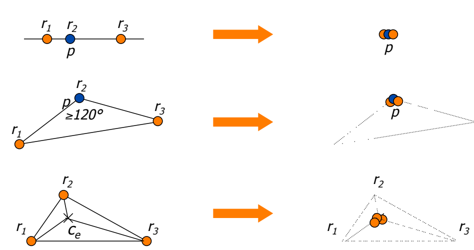
Gathering, *n=3*
(Unlimited Visibility, no agreement)



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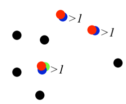
General Schema

- Use of Multiplicity Detection
  - n=3,4 (and even with the use of Weber Point)

Is there 1 or more than 1 robot at a point?



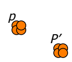
General Schema

The general idea of the solutions is based on multiplicity detection, as follows

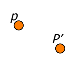
1. At the beginning, robots on distinct positions
2. Get a scenario where there is only one point *p* with multiplicity greater than one
3. All robots move towards *p*

Multiplicity Detection

If the robots cannot detect multiplicities…



is as….

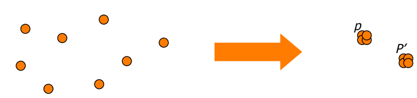


…the proposed solutions do not work!!!!

Multiplicity Detection

For n=2, the problem is not solvable (*Suzuki et al., 1999*)!

It is possible to design an adversary that lets the robots occupy two distinct positions on the plane in a finite number of cycles…



Multiplicity Detection

….hence….

Problem not solvable with n=2

+

No multiplicity detection

⬇

Problem not solvable for any n!

Gathering

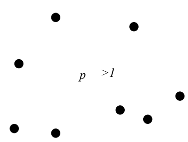
No agreement on the local coordinate systems, and ***oblivious*** robots….

⬇

[TCS 2007]
Necessary Condition: Multiplicity Detection!
(in SSYNC, hence in ASYNC)

The Main Idea (ICALP 2003)

- All distinct positions in initial configuration
- Some robots gather at a point *p*
- Point *p* is unique point with multiplicity >1
- All robots move to *p*



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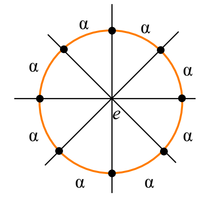
A Special Case

The robots can be in a totally symmetric configuration.



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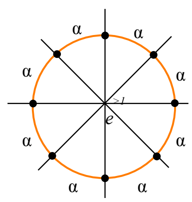
Equiangular Configurations

- All adjacent robots have angle α w.r.t. center e
- Center e is easy to compute
- Move all robots towards e



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Algorithm Skeleton

If strict multiplicity: move there

Else If equiangular: move to center

Else elect some robots to gather

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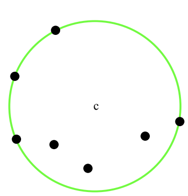
Smallest Enclosing Circle

- Unique
- Easy to compute
- Invariant if suitable robots move



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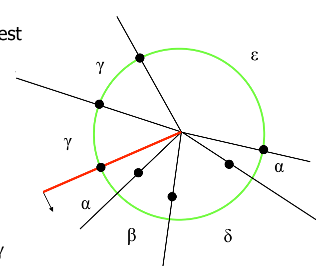
String of Angles

- W.r.t. center of smallest enclosing circle
- Circular string
- Can contain 0's



Lex. minimum: αβδαεγγ

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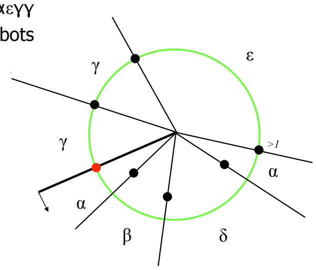
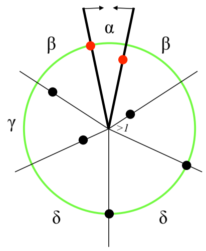
1 Starting Position

- Lex. min string: αβδαεγγ
- Unique ordering of robots



2 Starting Positions

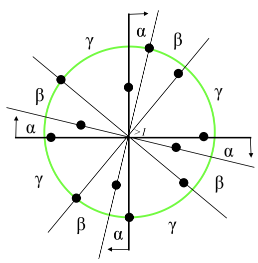
- Palindrome: αβγδδγβ



- or Periodic: αβγδ αβγδ

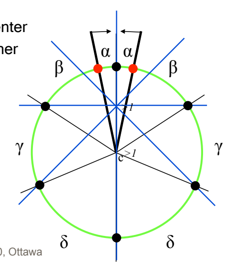
3..*n*-1 Starting Positions

- Periodic: αβγ αβγ …



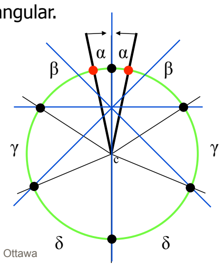
Problem: Case Switches

The algorithm:
If strict multiplicity: move there
Else If equiangular: move to center
Else elect some robots to gather



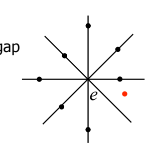
Cautious Movements

The moving robots stop at any critical point where the configuration becomes equiangular.



Finding Critical Points

- 1 starting position:
  is there center of equiangularity with 1 gap



- 2 starting positions:
  same with 2 gaps
- 3..n-1 starting positions:
  cannot generate equiangular configurations

Other Studies on Gathering

- Cieliebak, LATIN 2004
  - Non-oblivious robots, ASYNC
  - No multiplicity detection
- Gathering via Center of Gravity
  - Peleg et al.
- Gathering with faulty robots

Other Studies on Gathering

- Gathering with dynamic compasses
  - Katayama et al., SemiSync
- Gathering with limited visibility
  - Flocchini et al., TCS 2005, ASYNC

Problem 1.a: Gathering via CoG

Peleg et al.

Center-of-Gravity (CoG) algorithms

General approach:
In each cycle, the robots:
1. calculate some median position of the group
2. move towards that position

Natural variant:
Use the Center-of-Gravity (CoG)
(a.k.a. center of mass / barycenter)
of the robot group $\vec{c}[t] = \frac{1}{N}\sum_{i=1}^{N} \vec{r}_i[t]$

Note

- The analysis is performed in a d-dimensional space
- Easy consequence: convergence for $n=2$ robots using CoG algorithm

Analyzing CoG algorithm

In fully synchronous model: easy to analyze

In semi-synchronous / asynchronous model (more involved):

- Robots take measurements at different times, including while other robots are in movement
- Might cause oscillatory effects on the CoGs calculated by the various robots
- Might cause robots to pass each other by

Advantages of CoG algorithm

- Requires simple & efficient calculation - simple hardware, low computational effort.
- Applies to 1/2/3 dimensions and any # of robots.
- Bounded and simple-to-calculate rounding error
- Oblivious (i.e., requires no memory of previous actions & positions), hence
  - Memory-efficient
  - Self-stabilizing (i.e., finite number of transient errors cannot prevent eventual convergence).
- Prevents deadlocks (i.e., every robot can move at any given position unless already at center of gravity)

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Results

- CoG algorithm is correct in both the semi-synchronous and asynchronous model, for any # of robots

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Notation

Assume: Robots reside on x-axis.
(Handle each axis separately)

$r_i[t]$ = location of robot i at time t

$c_i[t]$ = CoG last calculated by robot i prior to time t

$c[t]$ = True CoG at time t

$H[t]$ = convex hull (smallest containing interval) of all $r_i[t]$ & $c_i[t]$

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Monotonicity of convex hull

Lemma: $H[t]$ cannot increase in time.

Lemma: In ASYNC, in any execution of CoG algorithm, over any $O(n^2)$ time interval, the convex hull of robot locations + CoGs is halved (in each dimension separately).

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Semi-synchronous model

Lemma:

In any execution of CoG algorithm, over any $O(n)$ time interval, the convex hull of robots + CoGs is halved (in each dimension separately).

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Fully synchronous model

Lemma: In any execution of CoG algorithm, robots achieve gathering in $4\ h[0]\ d^{3/2}$ time.

d: #dimensions
h[0]: max width of H[0]

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Problem 1.b: Self-stabilizing Deterministic Gathering

Petit et al., ALGOSENSORS 2009

We know that....

*All solutions so far assume that the robots start from **distinct** positions*

That is, even if the robots are oblivious, the solutions are not truly self-stabilizing

Petit et al. presented a deterministic protocol for solving the self-stabilizing gathering

- SSYNC
- Multiplicity Detection

We know that....

We know that the problem is unsolvable for 2 robots in SSYNC; hence, it is also unsolvable for an even number or robots

- The robots occupy at the beginning only two distinct positions on the plane, with n/2 robots on each position

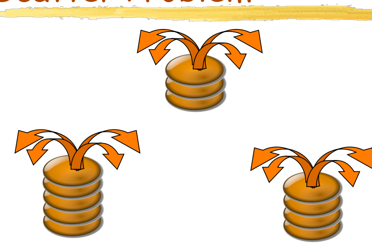
We know that....

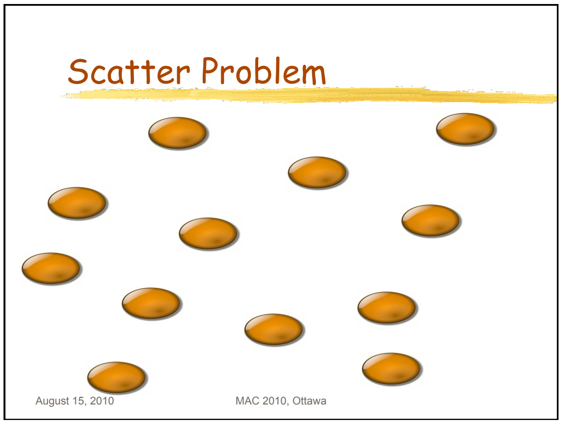
Petit et al presented a deterministic protocol for solving the (self-stabilizing) gathering for an odd number of robots, starting from any configuration

- SSYNC
- Strong Multiplicity Detection

Problem 2: Scattering Petit et. al., FUN 2007

Scatter Problem




Scatter Problem
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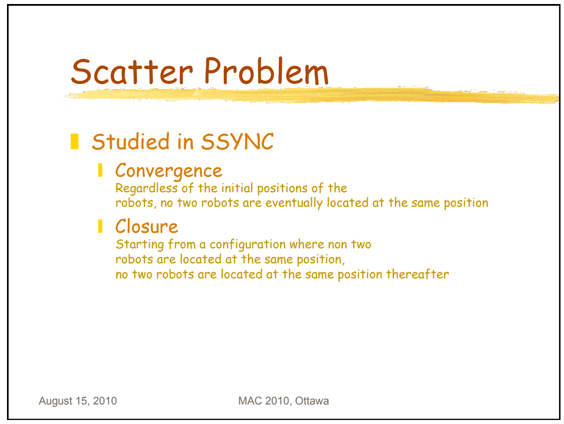
Scatter Problem
Studied in SSYNC
Convergence
Regardless of the initial positions of the robots, no two robots are eventually located at the same position
Closure
Starting from a configuration where non two robots are located at the same position, no two robots are located at the same position thereafter
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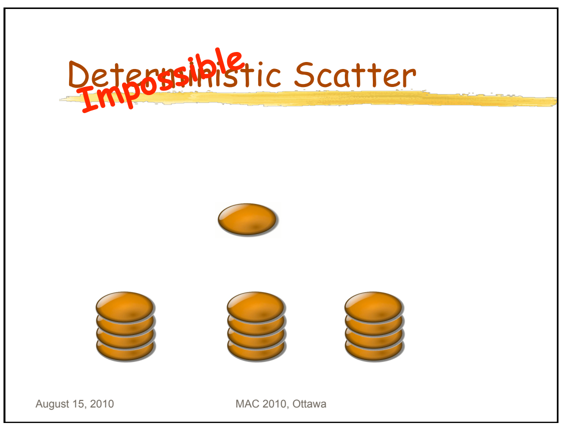
Deterministic Scatter
Impossible
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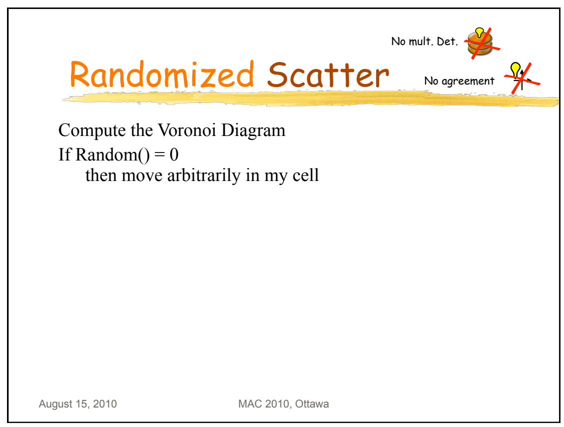
No mult. Det.
Randomized Scatter
No agreement
Compute the Voronoi Diagram
If Random() = 0
then move arbitrarily in my cell
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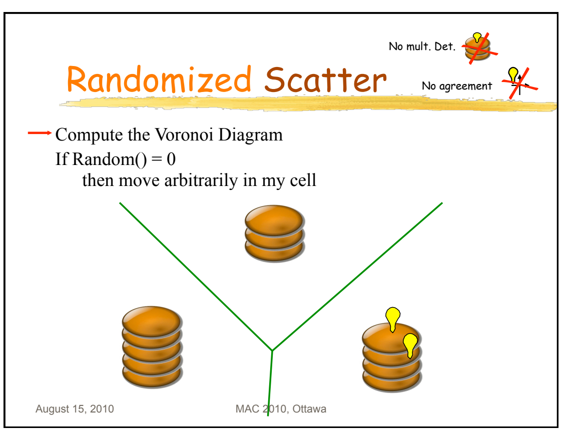
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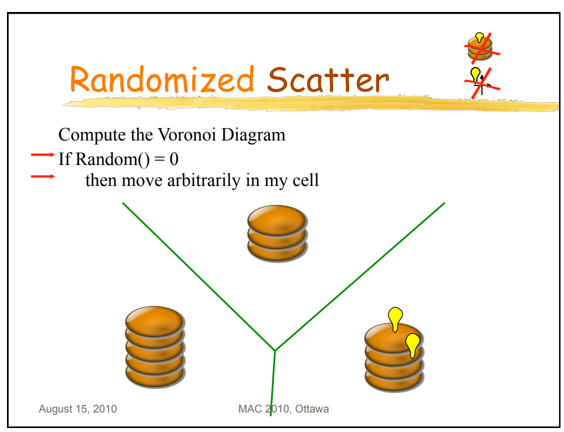
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Randomized Scatter

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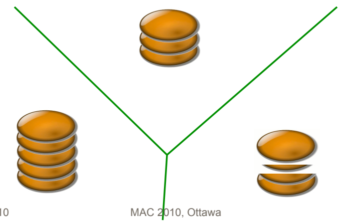

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If Random() = 0
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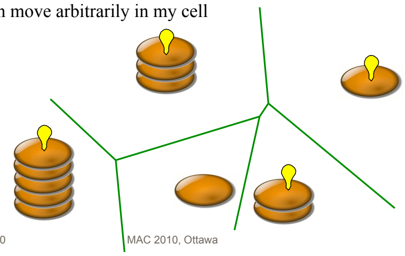

Randomized Scatter

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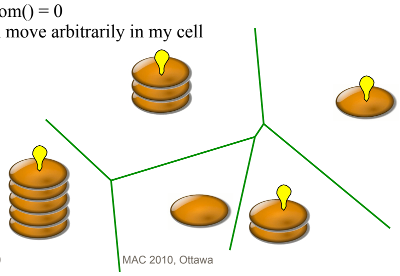

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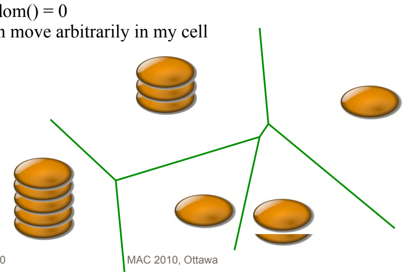
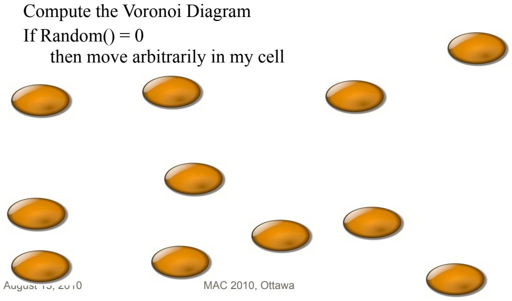


Randomized Scatter

Compute the Voronoi Diagram
If Random() = 0
then move arbitrarily in my cell



Randomized Scatter

- It could be used as a starting procedure for using previous gathering or arbitrary pattern formation
  - Multiplicity detection is necessary to switch
  - Eliminates the initial condition of having "distinct position"
  - Randomized Self-Stabilizing Solutions

Problem 3: Flocking

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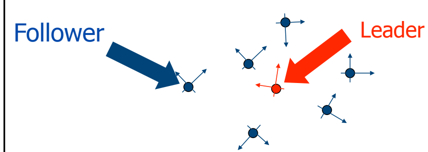
Flocking
Unlimited Visibility



Followers recognize Leader
No Agreement on Local Axes

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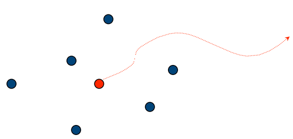
Flocking
Unlimited Visibility



Leader acts independently (e.g., human driven)

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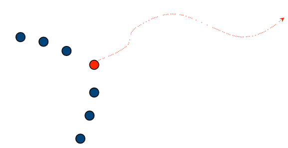
Flocking
Unlimited Visibility



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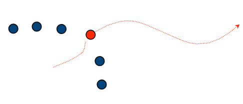
Flocking
Unlimited Visibility



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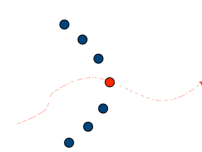
Flocking
Unlimited Visibility



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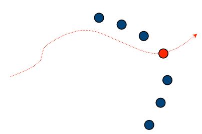
Flocking
Unlimited Visibility



Assumption

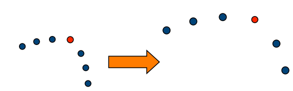
Time spent in *Look* and *Compute* is negligible w.r.t. the time spent in *Move*

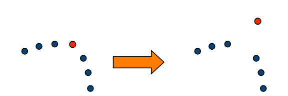
The constraints

- **No** shared coordinate system
- **No** way to observe direction of movement
- **No** common velocity
- **Common** pattern
  - In order for the problem to be significant!

Necessary conditions

- Common distance unit
  - Otherwise, the followers could scale the pattern instead of following the leader
- Fast enough
  - The leader cannot be faster than the followers

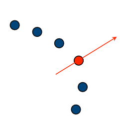




The Solution (Dam 2004)

Followers do not know the path to follow in advance

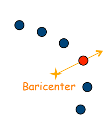
The algorithm lets Followers only form patterns that are symmetric w.r.t. direction of movement of the Leader



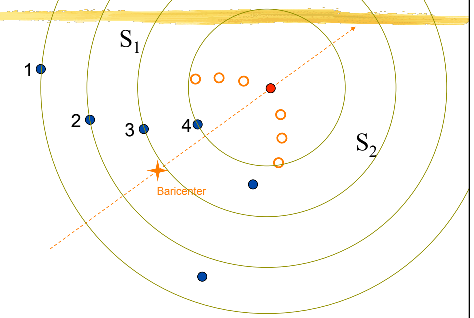
The Solution (Dam 2004)

Followers need a way to approximate the direction of movement of the Leader

Estimated direction of movement: Given by axis passing through baricenter of Followers' positions and Leader's position



The Algorithm (Dam 2004)



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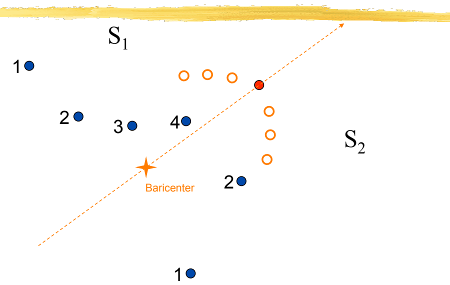
The Algorithm (Dam 2004)



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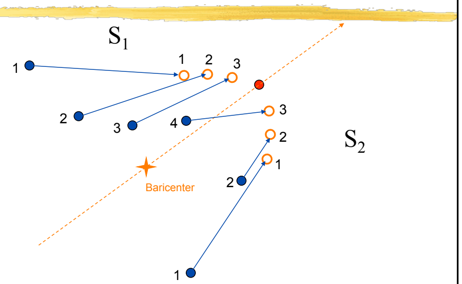
The Algorithm (Dam 2004)



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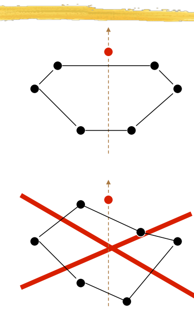
Fleet symmetry

- The pattern must be symmetric wrt the direction of movement of the leader
- Other patterns may be formed with more agreement (e.g., 1 axis)
  - Not studied yet!!



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A few quirks

- Stability: ships may have to give way
- Limits on the angular velocity of the leader
- Real heading of the leader (and thus formation) different from estimated

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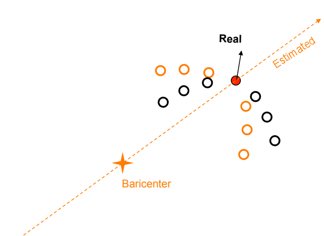
Real vs estimated heading



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Measures

- Given a set of ships F and a set of points Z (the pattern), we define:

$$\Delta_{F,Z}(t) = \min_{\pi \in \Pi} \sum_{i=1}^{|F|} d(f_i(t), z_{\pi_i}(t))$$

- Experimental measures:
  - Distance from estimated formation (Δ_e)
  - Distance from real formation (Δ_r)

Experimental results

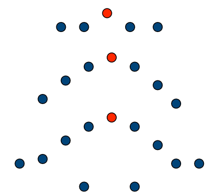
Tests of the solution with four formations:

Line (4)

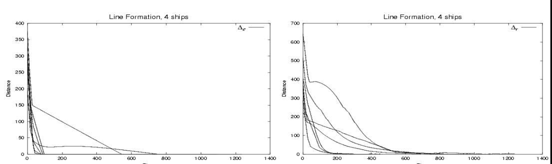
Wedge (6)

Spread (10)

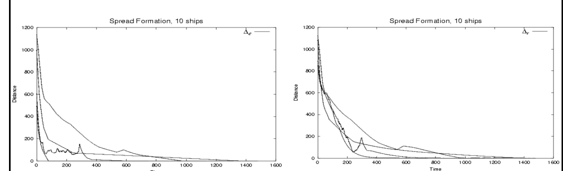
Random (2-8)



Experimental results



Experimental results



Experimental results

Leader

Problem 4: Intruder

The intruder problem

- An **intruder** is trying to sneak through a restricted area
- A number of autonomous units (robotic **cops**) is patrolling the area
- The cops have to **surround** the intruder


The intruder problem

- Example: sensible infrastructures
  - Airfield runway
  - Logistic compound
  - Dam or power plant
- Example: hostile area
  - Battlefield
  - Police operation

The cops

- Units must be truly **autonomous**
  - Completely asynchronous
  - Undistinguishable (i.e., no IDs)
  - No explicit communications (i.e., no radio)
  - No shared knowledge
    - No common compass
    - No common chirality

The cops

- Units must be truly **autonomous**
  - Completely asynchronous
  - Undistinguishable (i.e., no IDs)
  - No explicit communications (i.e., no radio)
  - No shared knowledge
    - No common compass
    - No common chirality
- Algorithm must work with a **variable number** of cops
  - Cops could be knocked-off by the intruder

Computational model

- We consider an infinite plane
- Both the intruder and the cops are modeled as units that can freely move on the plane

- All cops move according to a given **algorithm** (the same for all the units)
- The intruder moves **independently** from other units; its course is not known in advance

Computational model

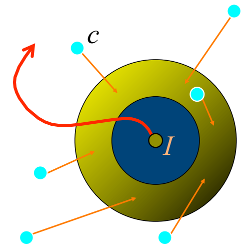
- Cops have **sensors** that report the **positions** of the intruder and of other cops
- Cops are **oblivious** – they have no memory, and do not rely on stored information about the past

Computational model

- As in the flocking, we assume that
  - Time spent in *Look* and *Compute* is negligible w.r.t. the time spent in *Move*

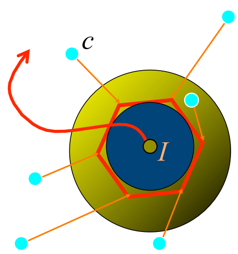
Formalizing the problem

- The cops must occupy a **ring** around the intruder:
  $r_1 \le \mathrm{dist}(c, I) \le r_2$
- The cops must be evenly spaced, minimazing the maximal "**escape hole**" in the ring

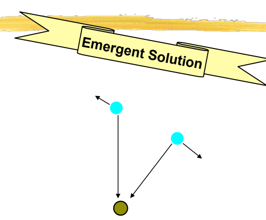


Formalizing the problem

- Both conditions can be met by forming a regular n-gon of characteristic angle $2\pi/n$ and radius r_1



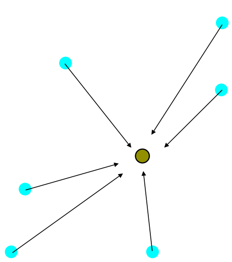
Two Algorithms: Heuristic (FUN 2004)



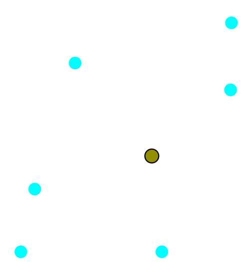
Heuristic approach

- All robots are subject to two forces:
  - Attractive, towards the enemy
  - Repulsive, mutual
- Parameters are tuned so that the aequilibrium is a solution for the problem

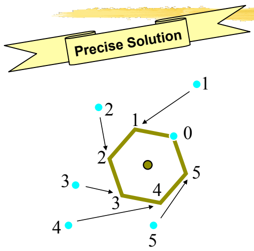
The HEUR-S Algorithm



The HEUR-S Algorithm



Two Algorithms: LAT



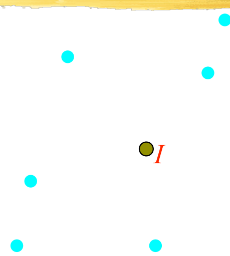
Algorithmic approach

- The robots reach an agreement on their ordering
- Each one establishes its own target
- They reach the target (taking care not to overtake each other)

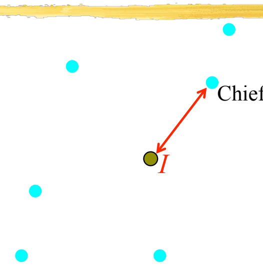
The LAT algorithm (idea)

- The closest cop to the intruder is identified and declared *Chief*

The LAT algorithm (idea)



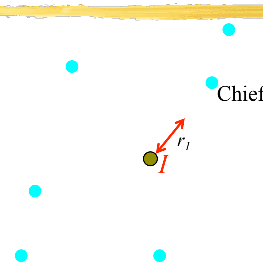
The LAT algorithm (idea)



The LAT algorithm (idea)

- The closest cop to the intruder is identified and declared *Chief*
- The Chief moves towards the intruder, up to a distance r_1

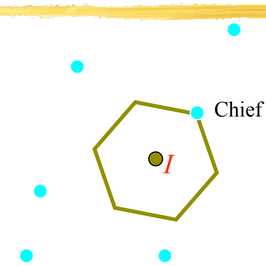
The LAT algorithm (idea)



The LAT algorithm (idea)

- The closest cop to the intruder is identified and declared *Chief*
- The Chief moves towards the intruder, up to a distance r_1
- The other cops scale and align the n-gon so that the center is on I and a vertex on the Chief

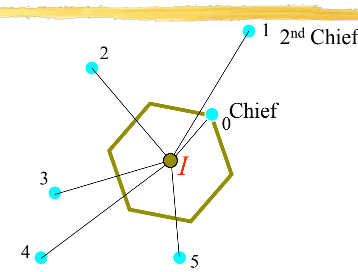
The LAT algorithm (idea)



The LAT algorithm (idea)

- The closest cop to the intruder is identified and declared *Chief*
- The Chief moves towards the intruder, up to a distance r_1
- The other cops scale and align the n-gon so that the center is on I and a vertex on the Chief
- All cops are lexicographically sorted according to their angle with I-Chief
  - Orientation is Chief → 2nd Chief

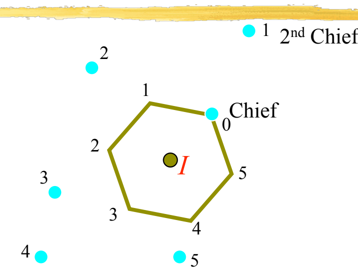
The LAT algorithm (idea)



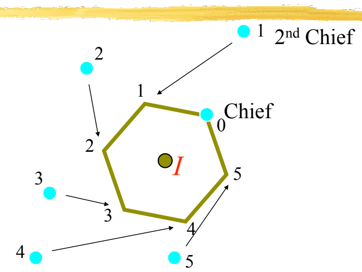
The LAT algorithm (idea)

- The closest cop to the intruder is identified and declared *Chief*
- The Chief moves towards the intruder, up to a distance r_1
- The other cops scale and align the n-gon so that the center is on I and a vertex on the Chief
- All cops are lexicographically sorted according to their angle with I-Chief
  - Orientation is Chief → 2nd Chief
- The i-th cop in the ordering moves (up to ε) toward the i-th vertex of the scaled and aligned n-gon

The LAT algorithm (idea)



The LAT algorithm (idea)



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Some pitfalls….

- Multiple candidate chiefs
  - All cops wait for the intruder to move, breaking the tie
- A cop may have to go to the opposite side of the ring
  - Perform a *sideway step* to avoid a change of Chief

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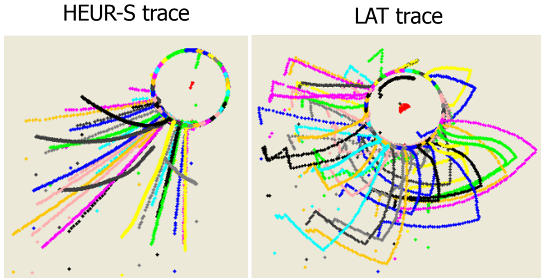
Two Algorithms

HEUR-S trace LAT trace



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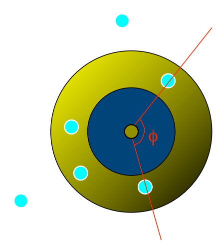
Evaluation of the algorithm

- Numerical simulations
- Two kind of measures:
  - What fraction of the cops is inside the target ring?
  - How large is the largest hole in the ring, w.r.t. the optimal hole?



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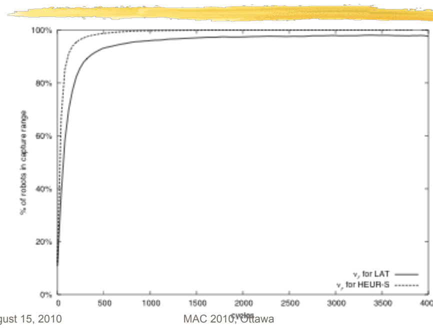
Fraction of Robots in the Capture Area



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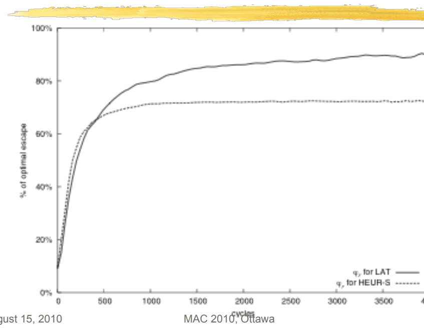
Size of Largest Hole (relative)



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Adaptiveness

- The algorithms adapts to dynamic changes in the number of cops
  - Cops can join
  - Cops can leave

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Fault Tolerance

- Robots could be blocked, knocked off by the enemy, or otherwise suffer **faults**
- We consider **transient** faults
  - A faulty robot stops moving, but continues sensing and computing
  - Fault model based on two parameters:
    - p_f – probability of occurrence of a fault
    - p_r – probability of resuming normal behaviour
- Faults occur indefinitely

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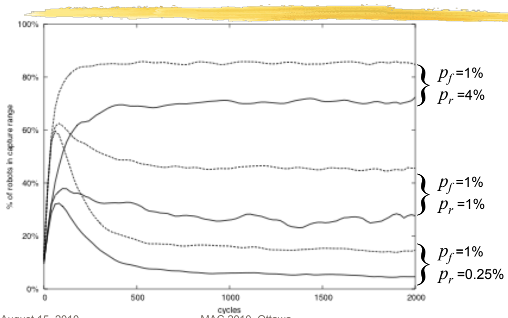
Robots in the Capture Area (in the presence of faults)



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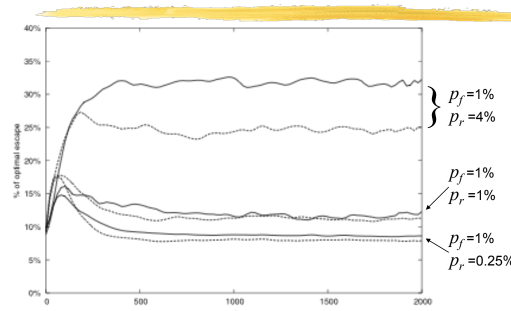
Size of the Largest Hole (in the presence of faults)



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Summary

- Gathering
  - ASYNC
  - CoG (ASYNC and SSYNC)
  - Self-Stabilizing Gathering in SSYNC
- Scattering (SSYNC)
- Flocking
- Intruder

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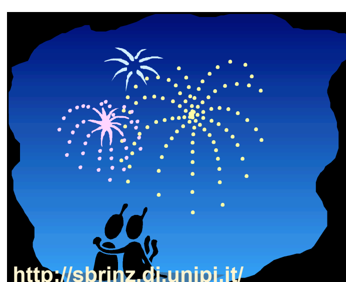

Thanks

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V. Gervasi – Italy
N. Santoro – Canada
P. Widmayer – Switzerland

THE END

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