A Look at Dependability and Synchrony in Distributed Mobile Robotic Systems:

Adding Some Pragmatism to Theory

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JST

Context / Motivation

- **Context**
  - Given: Multiple robots
  - Obtain: Single system
- **Requirements**
  - Deterministic solutions
  - Use little / no infrastructure
  - Weak / weaker / weakest assumptions
- **Characteristic**
  - Start from theory, move toward practice

Outline

- **Part I: Gathering problem**
  - Limited visibility
  - No communication
  - Compasses
- **Part II: Collision avoidance**
  - No visibility
  - Limited communication
- **Conclusion**

PART I

with:

- Samia Souissi (JAIST)
- Masafumi Yamashita (Kyushu Univ.)

Motivation

- **Context**
  - Autonomous robots
  - No infrastructure
  - No common knowledge (e.g., coordinate system)
- **Question**
  - What are the
    fundamental limits to robust coordination?

Gathering Problem

- **Gathering**
  - Set of robots located arbitrarily
    - ➥ All robots gathered at same location
- **Provides**
  - Agreement on common origin
- **Desired property**
  - Self-stabilization

System Model

- **Environment**
  - Euclidean plane
  - No landmarks
  - No obstacles
  - No boundaries

- **Robots**
  - Location: single point
  - Collocation possible; “no collisions”
  - Own coordinate system:
    origin, directions, unit distance

System Model

- **Interactions**
  - **Vision**: get position of robots
  - No explicit communication
  - No global coordinates

- **Activations**
  - Cycle: *Look - Compute - Move - ...Sleep...*
  - Deterministic algorithm
  - **Oblivious** (stateless)

    => self-stabilizing

System Model

- **Two Variants**
  - **Semi-Synchronous**

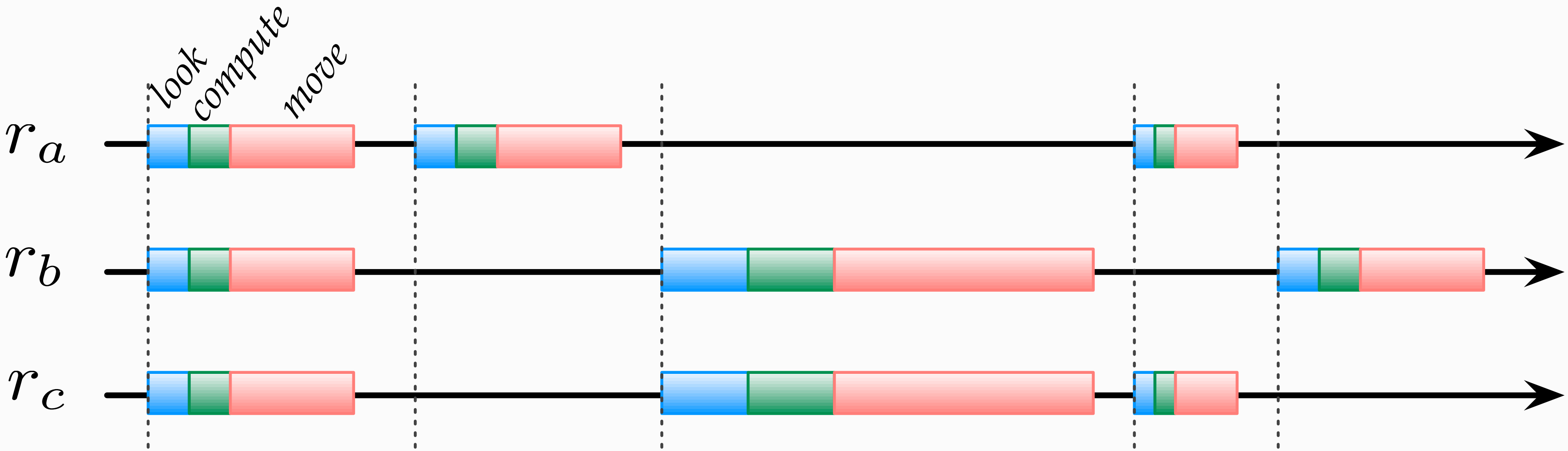
    [SY99] Suzuki, Yamashita. Distributed Anonymous Mobile Robots. *SIAM J. Comput.*, 28(4):1347–1363, 1999.

  - **Asynchronous**

    [FPSW05] Flocchini, Prencipe, Santoro, Widmayer. Gathering of asynchronous robots with limited visibility. *Theor. Comp. Sci.*, 337:147–168, 2005.

Semi-Synchronous

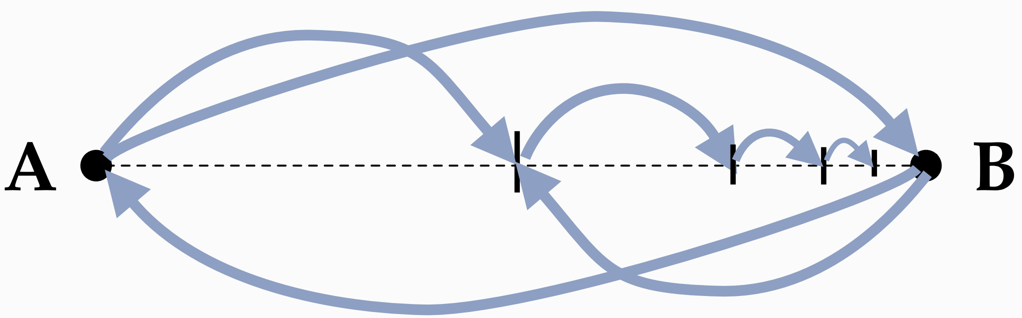
[SY99] Suzuki, Yamashita. Distributed Anonymous Mobile Robots. *SIAM J. Comput.*, 28(4): 1347–1363, 1999.



- **Activation Schedule**
  - Atomic cycle: *(Look - Compute - Move)*
  - Parallel: see same thing
  - Sequential: one see preceding movement

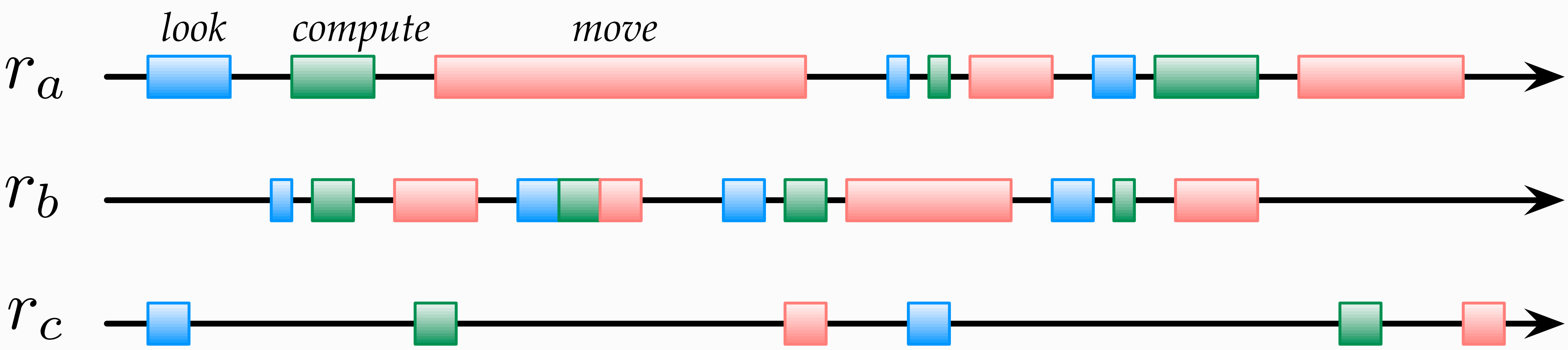
Gathering Problem

- **Goal**
  - From any configuration,
  - Eventually, all robots gather at single location
- **Difficulty: simple illustration**
  - Two robots A, B in semi-synchronous model



Asynchronous

[FPSW05] Flocchini, Prencipe, Santoro, Widmayer. Gathering of asynchronous robots with limited visibility. *Theor. Comp. Sci.*, 337:147–168, 2005.



- **No synchronization**
  - Can be seen while moving
  - Cannot anticipate others' moves

Convergence vs. Formation

- **Convergence**
  - Solve problem **asymptotically**
  - Trivial to achieve (e.g., barycenter)
- **Formation**
  - Solve problem **deterministically**
  - Difficult to achieve
  - Need to break symmetry

Gathering w/Limited Visibility

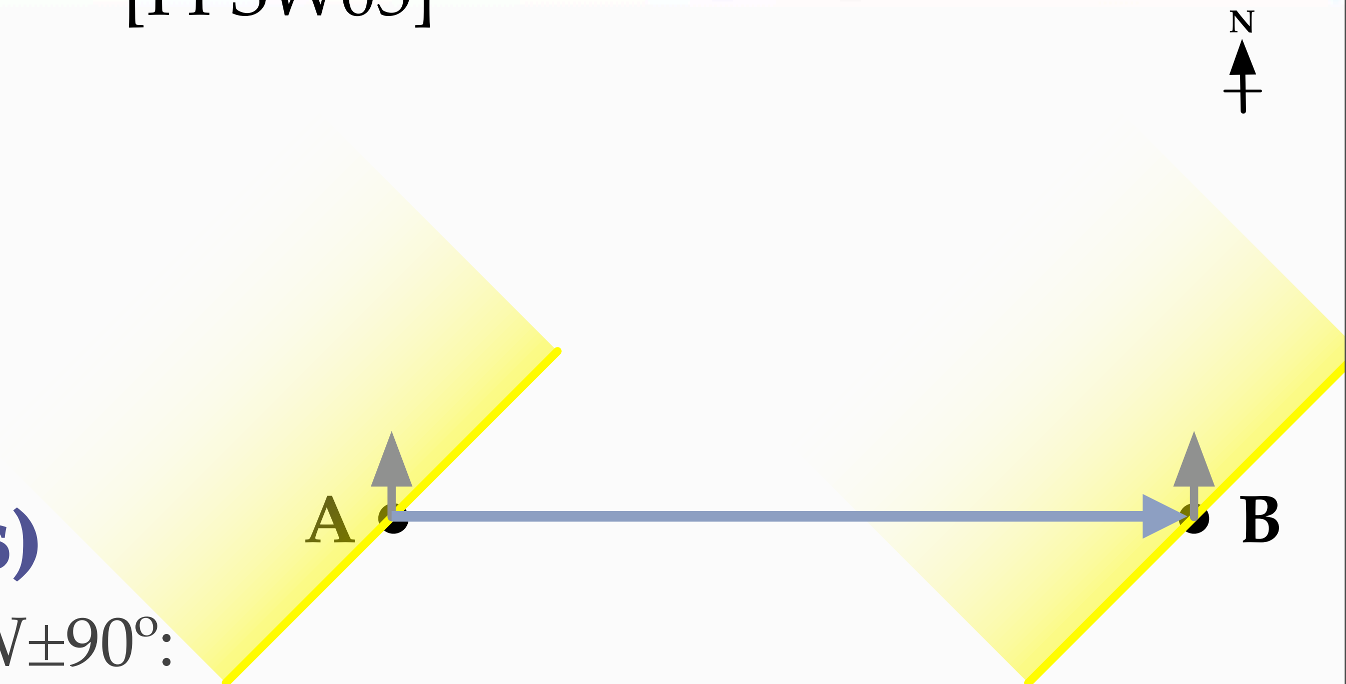
- **Assumption**
  - Visibility graph connected initially
- **Safety**
  - Keep visibility graph connected
- **Why?**
  - Partition unrecoverable
    - Oblivious robots
    - => forget about each other's existence
    - => gathering at more than one point (invalid)

Gathering Possible

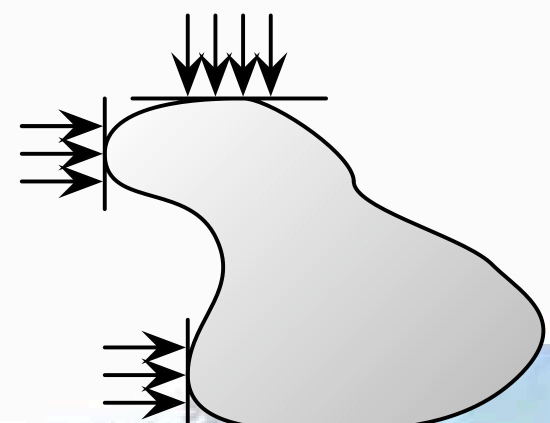
- **...in Semi-synchronous model**
  - proved in [SY99]
  - **Non-oblivious** robots
  - **Full** visibility
- **...in Asynchronous model**
  - proved in [FPSW05]
  - **Oblivious** robots
  - **Limited** visibility
  - **with compass** (i.e., shared orientation)

Gathering w/Compass

[FPSW05]



- **Role**
  - Break symmetry
- **Idea (2 robots)**
  - Other robot to NW±90º:
    - Wait
  - Otherwise
    - Move to other robot



Question

[SDY06]

- **What if**

  compasses are **unreliable?**

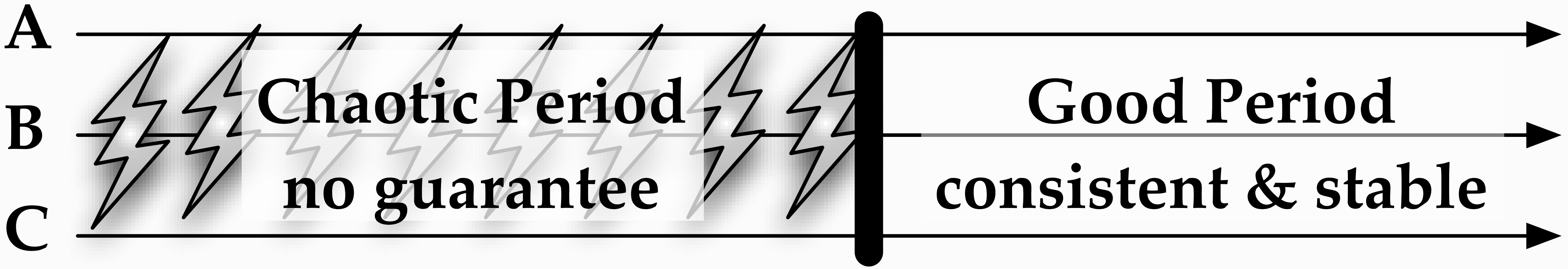
- **Especially**
  - Transient failures
  - Interference
  - Stabilization

Unreliable Compasses

- **Compass**
  - Function of (time, robot) -> direction
- **Perfect compasses**
  - Consistency: **all compasses point to the same direction**
  - Stability: **compasses never change**
- **Eventually-consistent Compasses**
  - There is a time (unknown) after which compasses are:

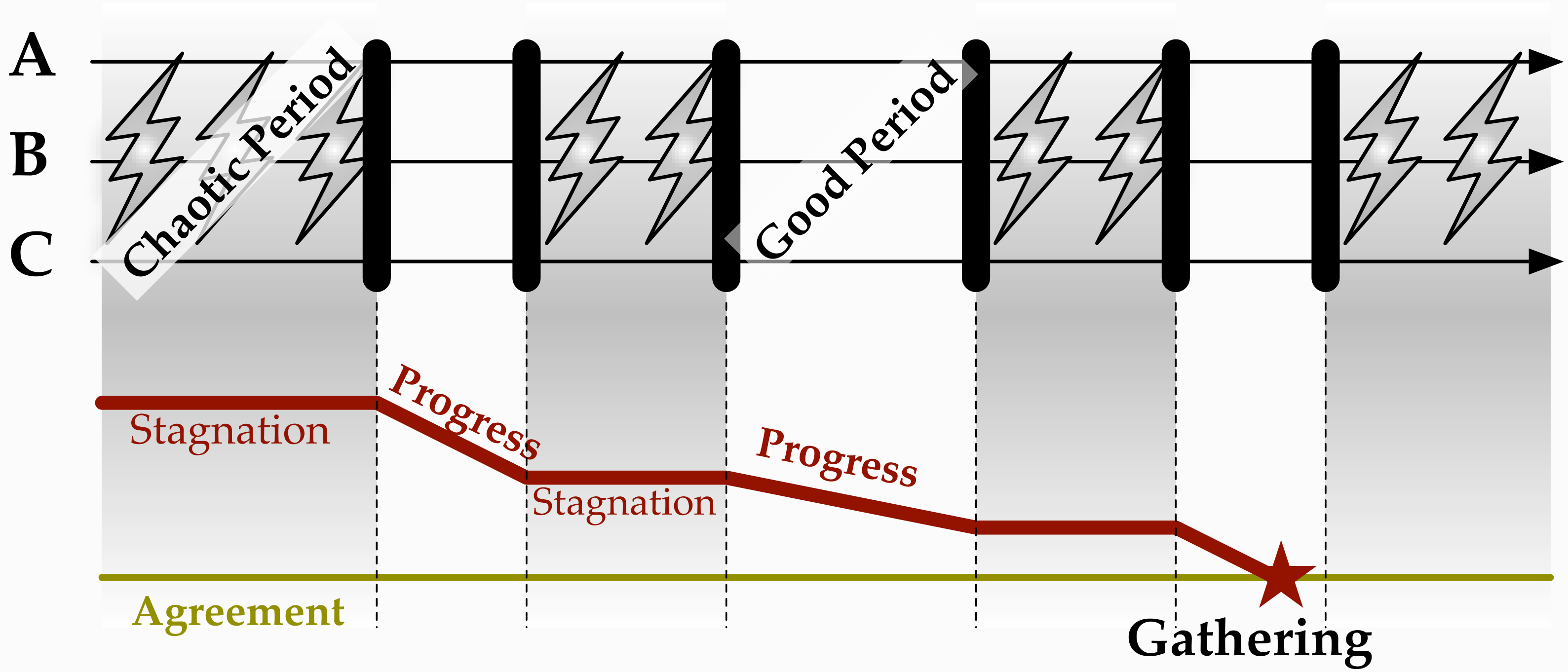
    consistent & stable

Unreliable Compasses



- **Chaotic period**
  - **Safety**: OK; **Progress**: *maybe*
- **Good period**
  - **Safety**: OK; **Progress**: OK

Unreliable Compasses



- **Practically speaking...**
  - Need good periods “long & frequent enough”
  - Algorithm tolerates unbounded number of transient failures
  -

Gathering w/Unreliable Comp.

		Perfect Compass	Eventual Compasses	No Compass
Asynch. Model	$n \geq 4$	[FPSW05] *([SDY06])*	Impossible	Impossible
	n=2,3		**[SDY06]**	
Semi-synchronous Model	$n \geq 3$			[SY99]
	$n = 2$			Impossible

Gathering w/Unreliable Comp.

- **Algorithm**
  - Use perfect compasses

    or
  - Use semi-synchrony

- **Impossible case**
  - Asynchronous, n >= 4
    - Algorithm [SDY06] => breaks visibility
    - Best possible: Admits deadlock situations

Some Future Work

- **Unreliable compasses**
  - with bounded imprecisions
- **Faulty robots**
  - Byzantine robots
- **Dynamic problems**
  - Flocking, etc...

PART II

with:

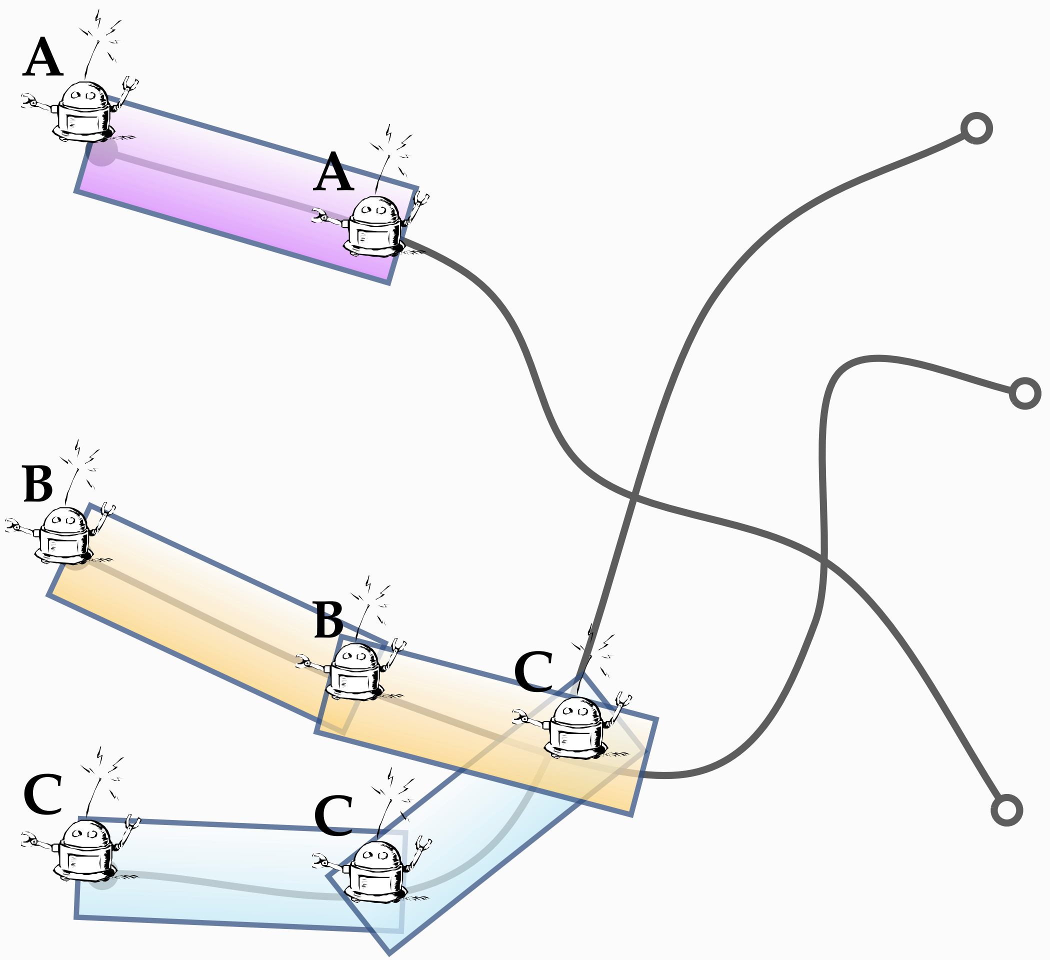
- Julien Cartigny (Univ. Limoges, France)
- Nak Young Chong (JAIST)
- Rami Yared (JAIST)
- Matthias Wiesmann (JAIST)

Motivating Context

- **Equipment**
  - 4 Pioneer-3 robots
    - Laptop
    - Wireless (WiFi; bluetooth)
    - Sonar (180º, 6-7m)
- **Objective**
  - Group movement without collisions
- **Desired Properties**
  - Decentralized solution
  - Fault-tolerance
  - Fail-safe behavior

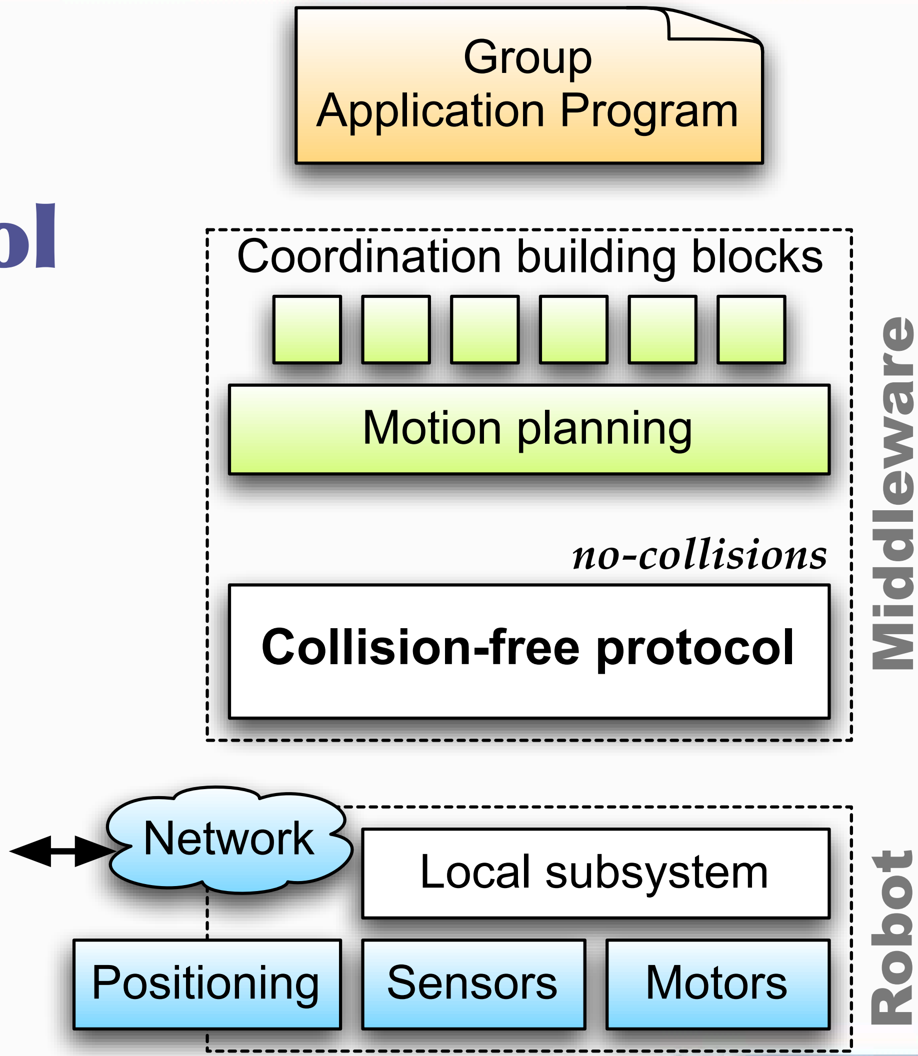
Path Reservation

- **Robot knows**
  - **own** destination / path
  - **own** location
  - information in messages
- **Does NOT know**
  - others' destinations
  - others' location
  - others' velocity
  - communication delays



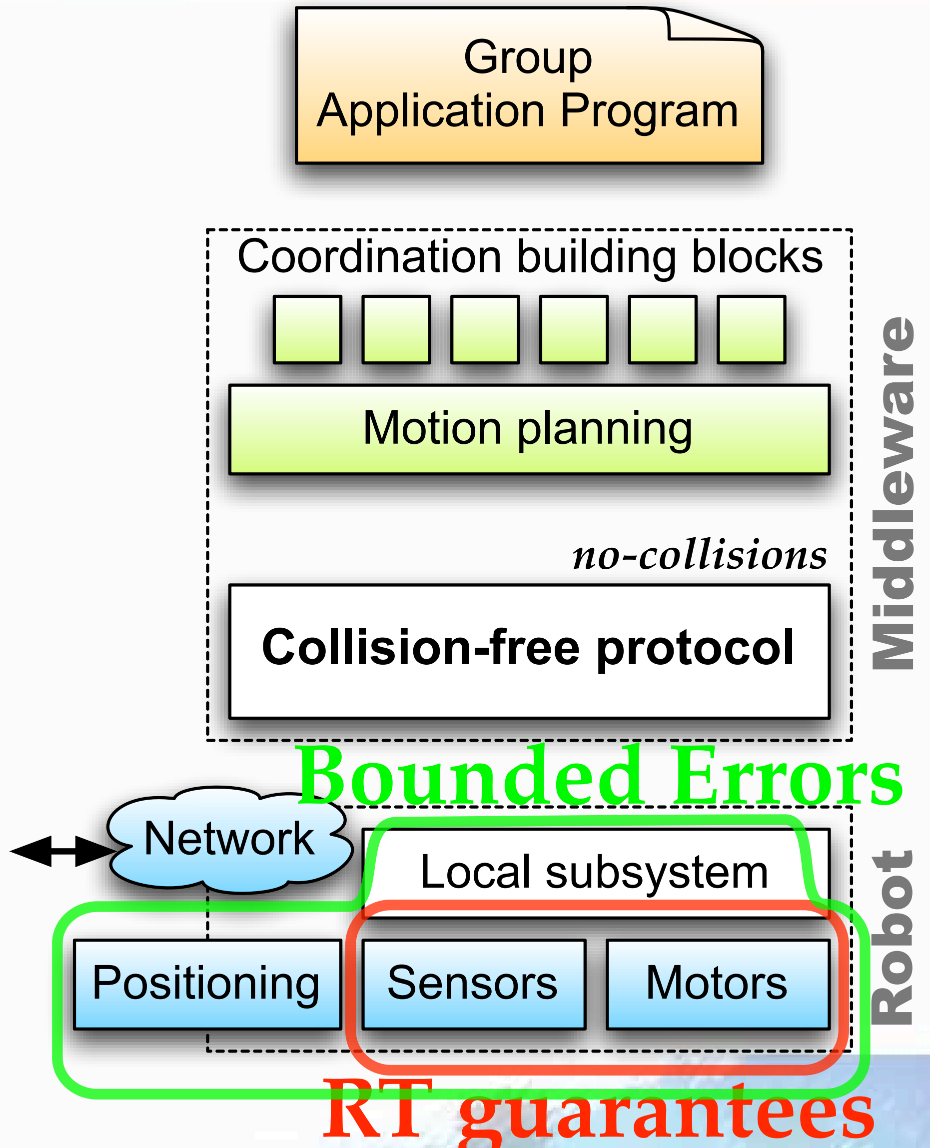
Architecture

- **Collision-free protocol**
  - Ensure no-collision
  - Fail-safe behavior
- **Local subsystem**
  - Individ. robot movements
  - Detect inert obstacles
  - Use sonars



Assumptions

- **Real-time**
  - Local subsystem
  - Sensors (sonars)
  - Motor control code



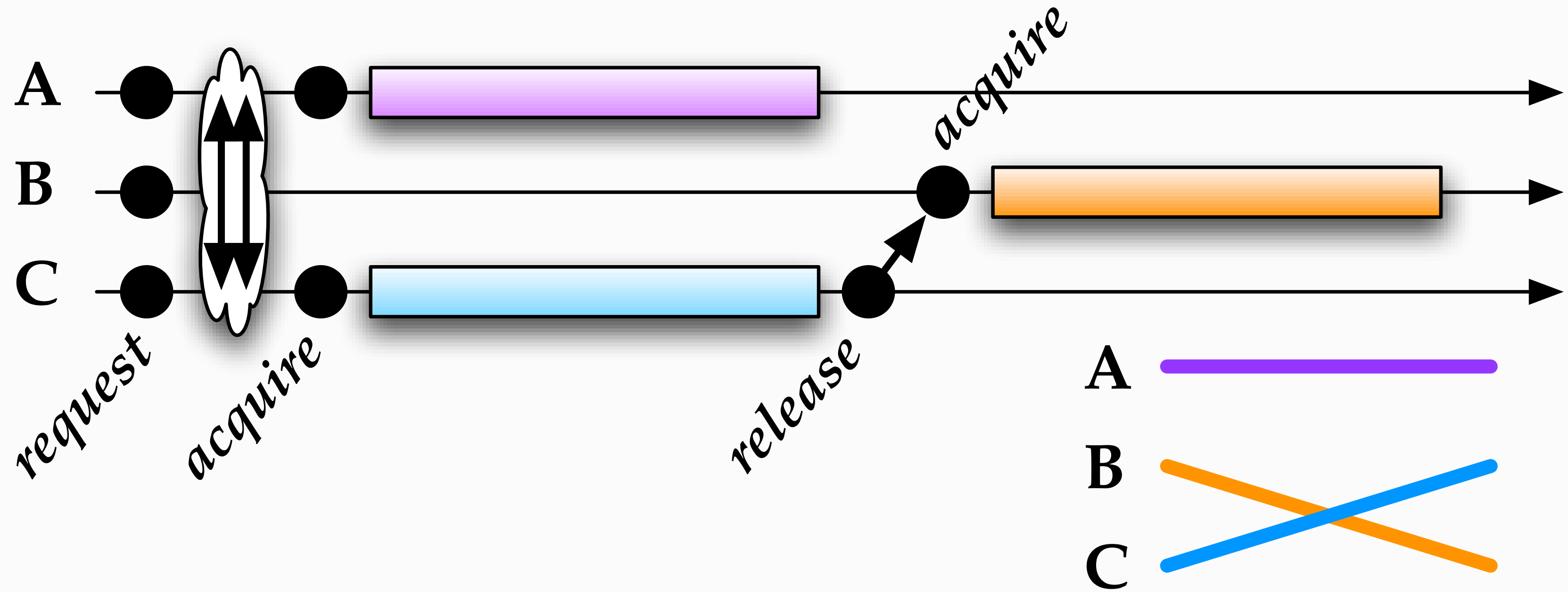
System Model

- **Robots**
  - Have footprint
  - No vision
  - Ad hoc wireless communication
- **Positioning System**
  - Global *x-y* referential
  - Robot can query asynchronously
  - Robots get **own position**
- **Communication**
  - Time-free
  - Two models: full, ad hoc

Path Reservation

- **Idea**
  - Similar to database locking
- **Primitives**
  - *acquire*: request lock on a zone
  - *release*: release zone
- **Benefits**
  - Prevent collisions
  - Provides some information on location

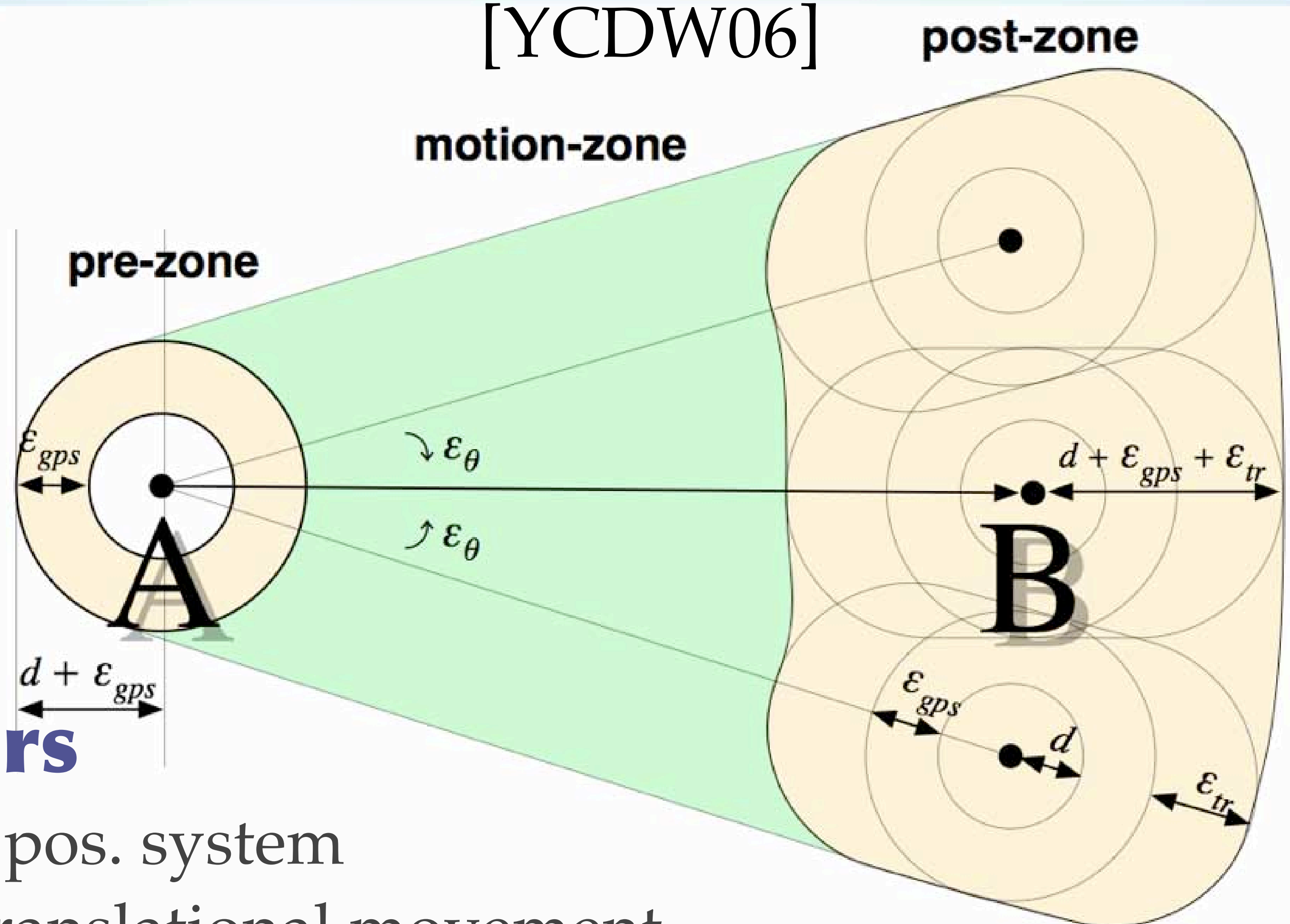
Path Reservation



- **Desired properties**
  - Mutual exclusion between conflicting requests
  - No starvation of requests (unless deadlock)

Anatomy of a Zone (errors)

[YCDW06]



- **Errors**
  - ε_{gps} : pos. system
  - ε_{tr} : translational movement
  - ε_{θ} : rotational movement (incl. sensors)

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Model 1: Fully connected

- **Model**
  - All robots "know" each other
  - All robots can communicate
  - Communication is reliable asynchronous
- **Purpose**
  - Few robots
  - Limited area
- **Benefit**
  - Simple, fault-tolerant solution

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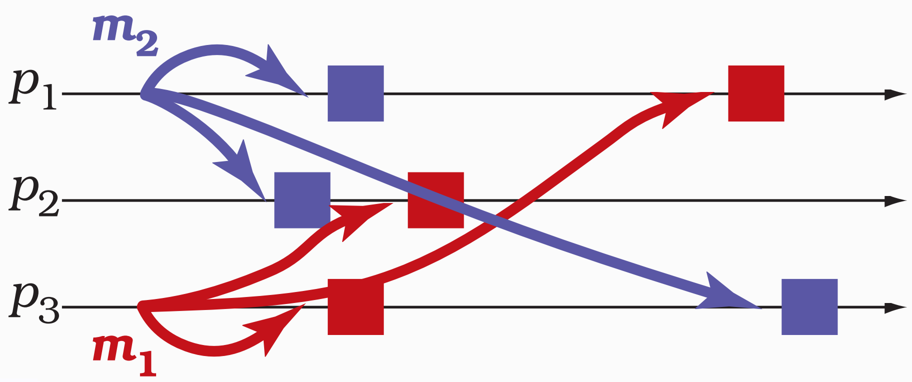
Model 1: Reservation

- **Idea**
  - Use **Total Order Broadcast** protocol

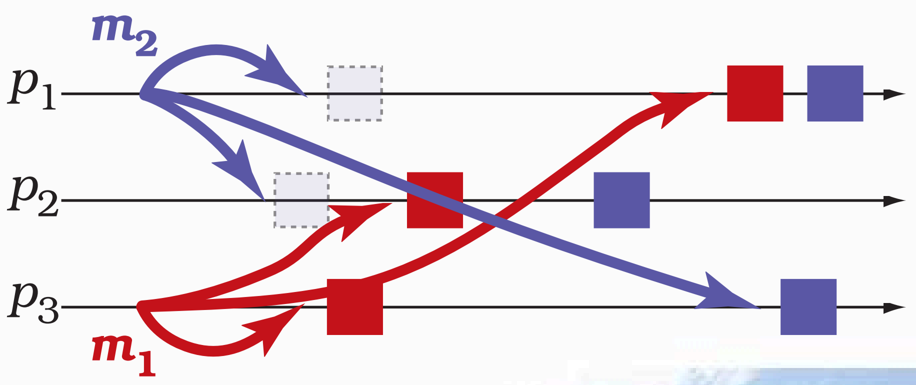
Total Order Broadcast

- Broadcast primitive
- Hosts deliver same sequence of messages

Ordinary Broadcast



Atomic Broadcast

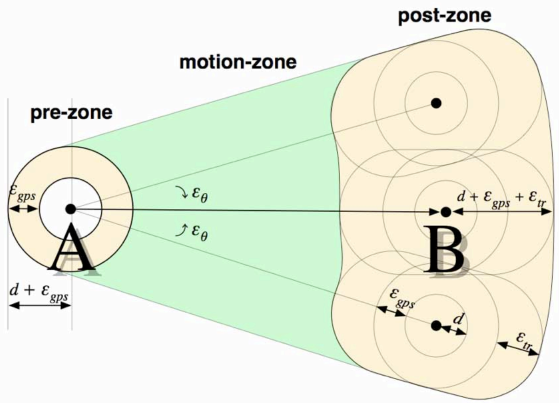


Model 1: Reservation

- **Idea**
  - Use of Total Order Broadcast
- **Advantages**
  - Well-known requirements
  - Many algorithms (see survey [DSU04])
  - Fault-tolerant solutions
    (e.g., with unreliable FDs & maj. correct hosts)
- **Synchrony assumption**
  - E.g., unreliable failure detectors
  - FAIL => liveness violation

Model 1: Protocol

- **To move**
  - Get own position
  - Compute zone Z
  - TO-bcast(*Request, Z*)
- **When TO-deliver (*Request, Z*)**
  - If conflict => put Z in pending requests
  - Else lock(Z)
- **When lock(*Z*)**
  - Move along Z
  - Wait until destination reached
  - Get own position; compute new pre-zone
  - R-bcast(*Release, Z - new pre-zone*)



Model 1: Drawbacks

- **Limited scalability**
  - Protocol involves all robots
  - ... regardless of actual location
- **Limited flexibility**
  - Requires initial knowledge of all robots
- **Energy consumption**
  - Requires coverage of whole area (or supplemented by routing)

Model 2: Ad hoc

[YCDW06]

- **Limited communication range**
  - Known to all robots: *D*

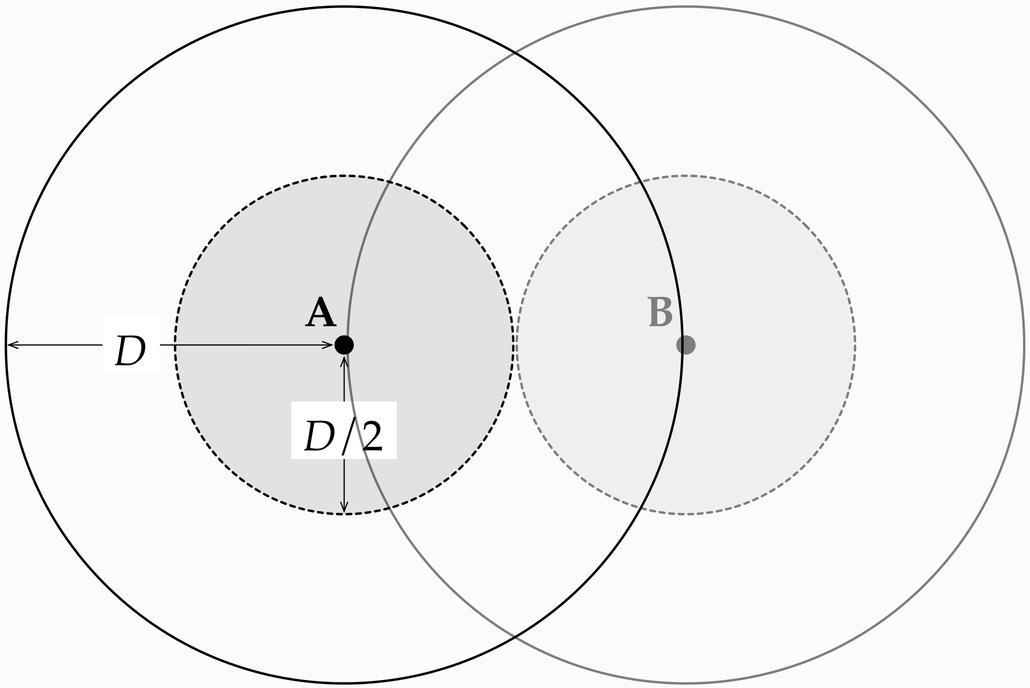
    (NB: *D* can be minimum of all ranges)
- **Asynchronous**
  - No bounds on message delays
    (e.g, because of retransmission).
- **Neighborhood discovery primitive**
  - Get set of **direct** neighbors
  - **Query** based primitive
  - **Stronger** guarantees

Model 2: Neighborhood Discovery

- **Primitive**
  - Query by robot *R* at time *t*
  - Return set *Neighbors(r,t)*

- **Query period**
  - From ***query*** to ***return***
  - For each robot *s'*; during query period:
    - *s'* in range => *s'* in *Neighbors(r)*
    - *s'* not in range => *s'* not in *Neighbors(r)*
    - *s'* partially in range => undetermined.

Model 2: Restrictions



- **Restriction**
  - Reservations within $D/2$ (- errors)
- **Ensures**
  - Cannot conflict without being "introduced"

Model 2: Discussion

- **Advantage**
  - Dynamic groups
  - Locality-preserving
  - Scalable
- **Drawback**
  - No fault-tolerant protocol yet
- **Synchrony assumption**
  - Neighborhood discovery
  - FAIL => safety violation

Future Directions

- **Protocol extension**
  - pipelining / interleaving
- **Parameter dimensioning**
  - robots density
  - robot speed / acceleration / braking distance
  - communication range
  - communication delays
  - errors

Conclusion

- **Part I**
  - Study limits of coordination
  - Tolerate faulty compasses
- **Part II**
  - Use communication & location
  - Reservation system
  - Full connected: simple, FT
  - Ad hoc: scalable, flexible
- **Theory: still a long way to go…**

References

- **Models**

  - [SY99] Suzuki, Yamashita. Distributed Anonymous Mobile Robots. *SIAM J. Comput.*, 28(4):1347–1363, 1999.
  - [FPSW05] Flocchini, Prencipe, Santoro, Widmayer. Gathering of asynchronous robots with limited visibility. *Theor. Comp. Sci.*, 337:147–168, 2005.

- **Gathering**

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- **Unreliable compasses**
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