Multirobot Systems

Lecture
Multirobot collision avoidance

Master Program in Robotics, Graphics and Computer Vision
Departamento de Informática e Ingeniería de Sistemas
Universidad de Zaragoza

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Introduction

- Real-time collision avoidance of mobile robots
  - They should sense their environment and react independently without communication or explicit coordination, as humans do

[Darpa challenge]

Introduction

- Multirobot motion planning
  - Global planning: Trajectory from initial to final location
  - Local planning: Collision avoidance up to a short time horizon

- Dynamic motion planning for a point in the plane, with bounded velocity and arbitrary many obstacles, is intractable (NP-hard)

Introduction

- Applications:
  - Autonomous cars
  - Computer games
  - Traffic engineering
  - Crowd simulation

- Warehouses with Kiva robots to deliver stacks of products

Introduction

- Applications:
  - Autonomous cars
  - Computer games
  - Traffic engineering
  - Crowd simulation

- Shibuya pedestrian crossing (Tokyo)
  - Around a million of people per day, 47 seconds to cross the street

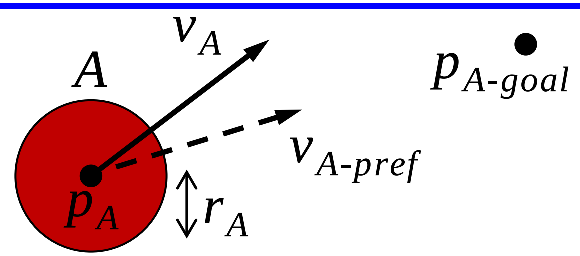
State of the art

- Collision avoidance approaches:
  - Dynamic motion planning
  - Local collision avoidance
- Some papers:
  - D. Fox, W. Burgard and S. Thrun, "The dynamic window approach to collision avoidance," in IEEE Robotics & Automation Magazine, vol. 4, no. 1, pp. 23-33, March 1997
  - L. Pallottino, V. G. Scordio, A. Bicchi and E. Frazzoli, "Decentralized cooperative policy for conflict resolution in multivehicle systems," in IEEE Transactions on Robotics, vol. 23, no. 6, pp. 1170-1183, Dec. 2007, doi: 10.1109/TRO.2007.909810.
  - P. Fiorini, Z. Shiller, "Motion planning in dynamic environments using velocity obstacles," The International Journal of Robotics Research. 1998;17(7):760-772.
  - J.L. Blanco, J. González and J.A. Fernández-Madrigal, "Extending obstacle avoidance methods through multiple parameter-space transformations," in Autonomous Robots, 24, 29-48 (2008). https://doi.org/10.1007/s10514-007-9062-7
  - **J. Snape, J. P. van den Berg, S. J. Guy, D. Manocha. "The hybrid reciprocal velocity obstacle," IEEE Transactions Robotics 27(4). 696-706 (2011)**
  - M. Rufli, J. Alonso-Mora and R. Siegwart, "Reciprocal collision avoidance with motion continuity constraints," in IEEE Transactions on Robotics, vol. 29, no. 4, pp. 899-912, Aug. 2013, doi: 10.1109/TRO.2013.2258733.
  - L. Wang, A. D. Ames and M. Egerstedt, "Safety barrier certificates for collisions-free multirobot systems," in IEEE Transactions on Robotics, vol. 33, no. 3, pp. 661-674, Jun. 2017

Problem definition

- Setup: Navigation in an environment with dynamic obstacles
  - Disc-shaped robots in the plane with fixed radius and a current velocity
    - Known to the robot and may be measured by the others
  - Dynamic and static obstacles
    - We assume they can be identified by each robot
  - Each robot has a goal location and a preferred speed
    - unknown to the other robots
  - No communications. No coordination
  - May assume the others use the same strategy for collision avoidance

Robot: A
Robot radius: r_A

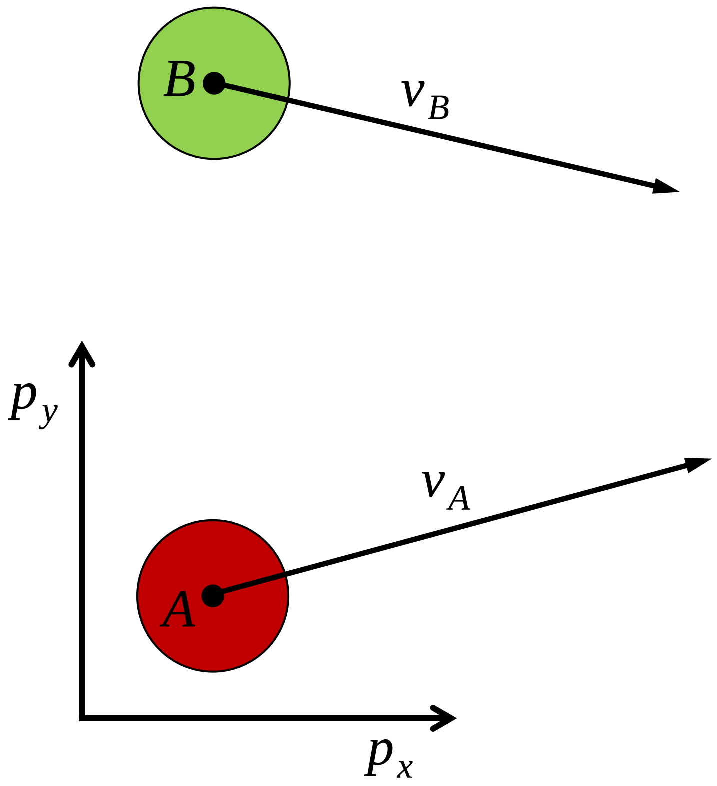


Current position: p_A
Goal position: $p_{A\text{-}goal}$
Current velocity: v_A
Preferred velocity: $v_{A\text{-}pref}$

- Problem:
  - Each robot computes a new velocity at each time step to move toward its goal without collisions with any other robots

Problem definition

- Given robots A and B moving in the plane, will they collide in ΔT?

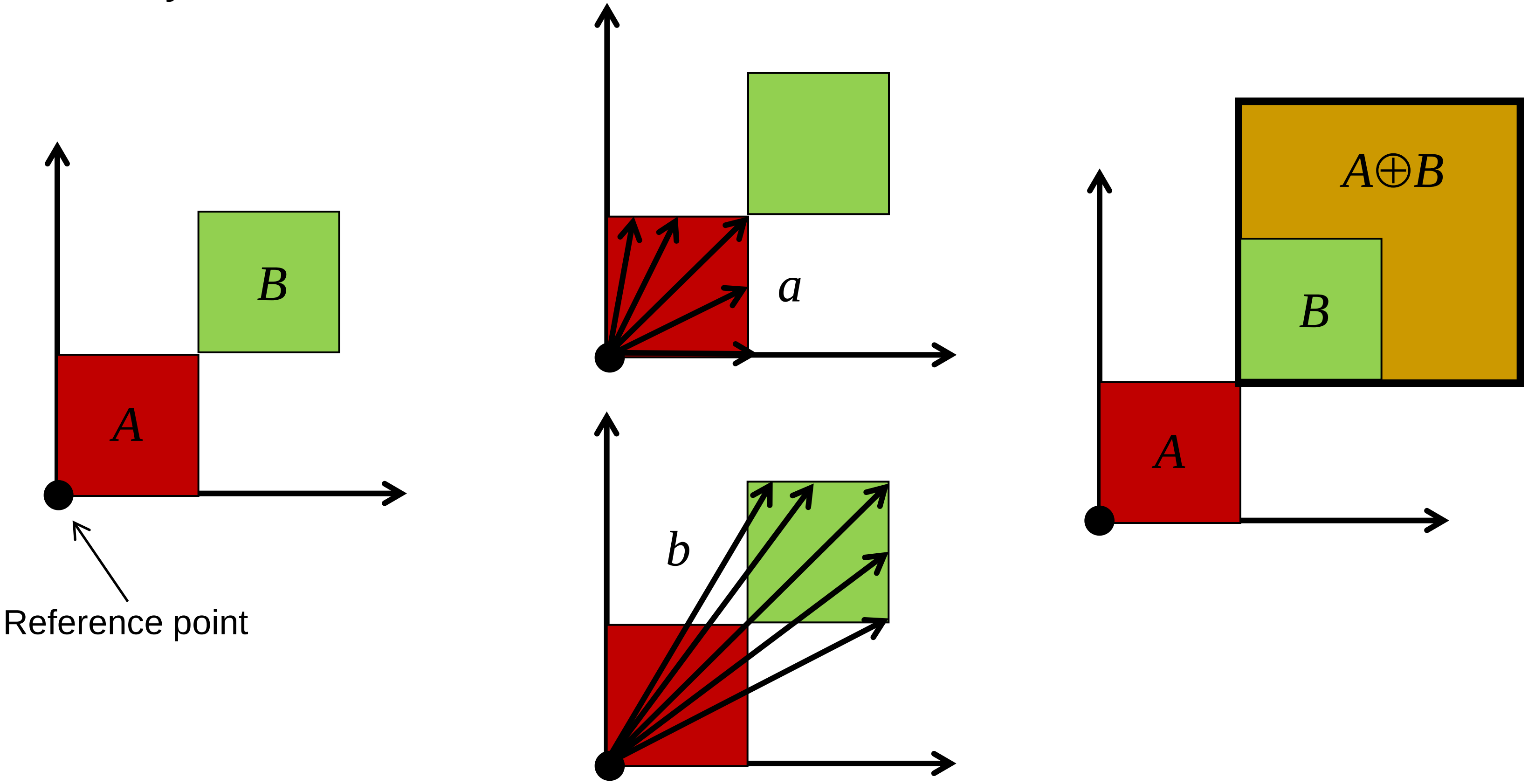


Velocity obstacle method

- Minkowski addition
  - Definition: is the sum of sets A and B in a vector space such that

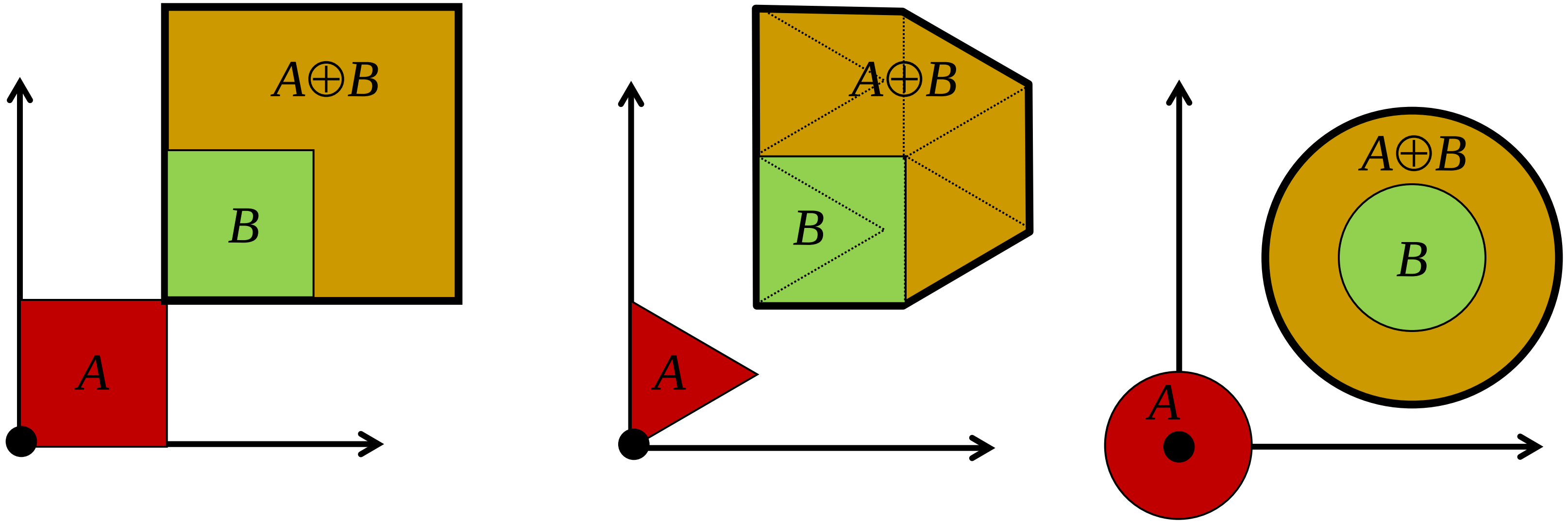
$$A \oplus B = \{\mathbf{a} + \mathbf{b} \,|\, \mathbf{a} \in A, \mathbf{b} \in B\}$$

  - May be referred as *dilation*



Velocity obstacle method

- Minkowski addition
  - Examples

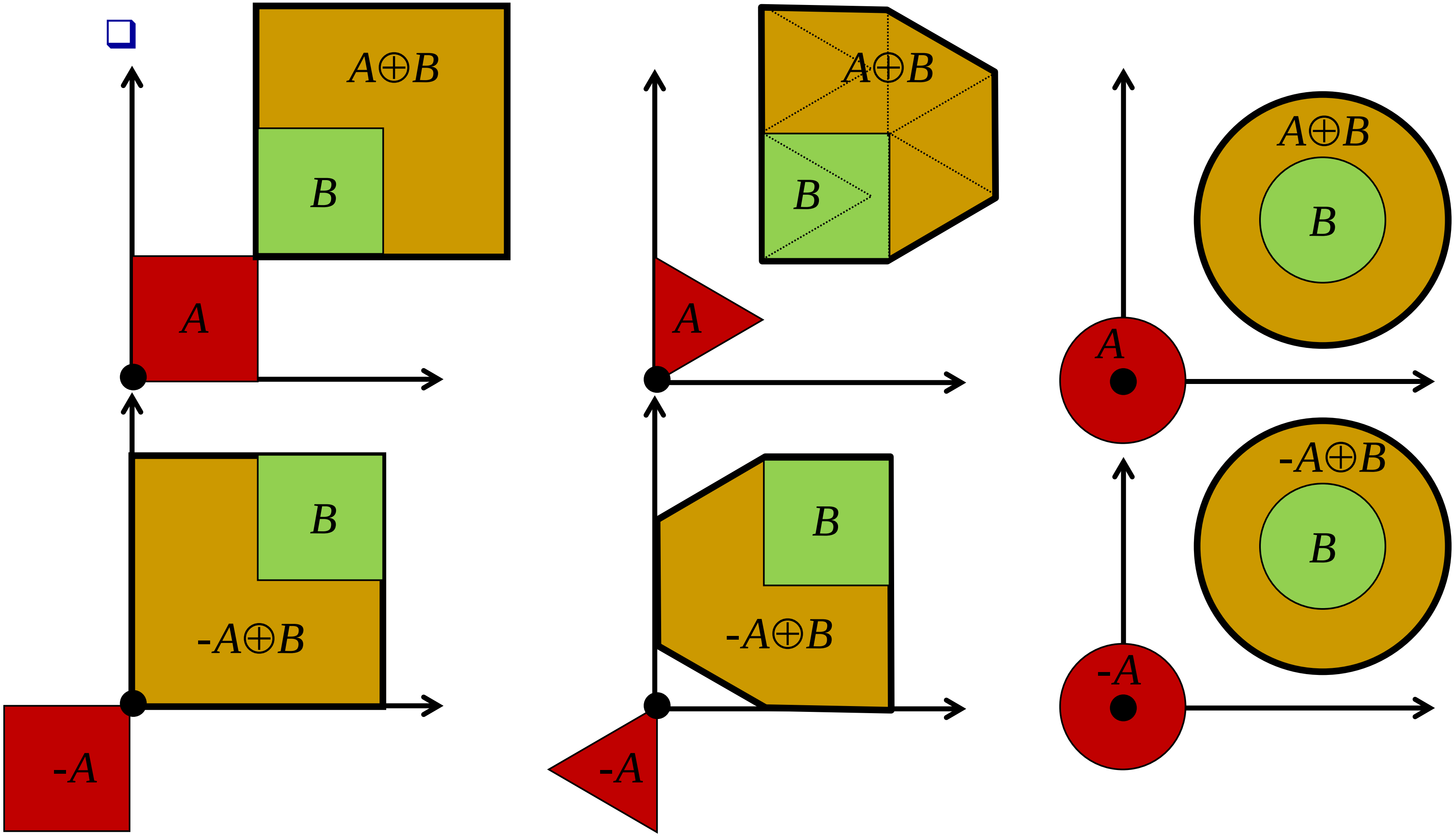


Velocity obstacle method

- Minkowski addition

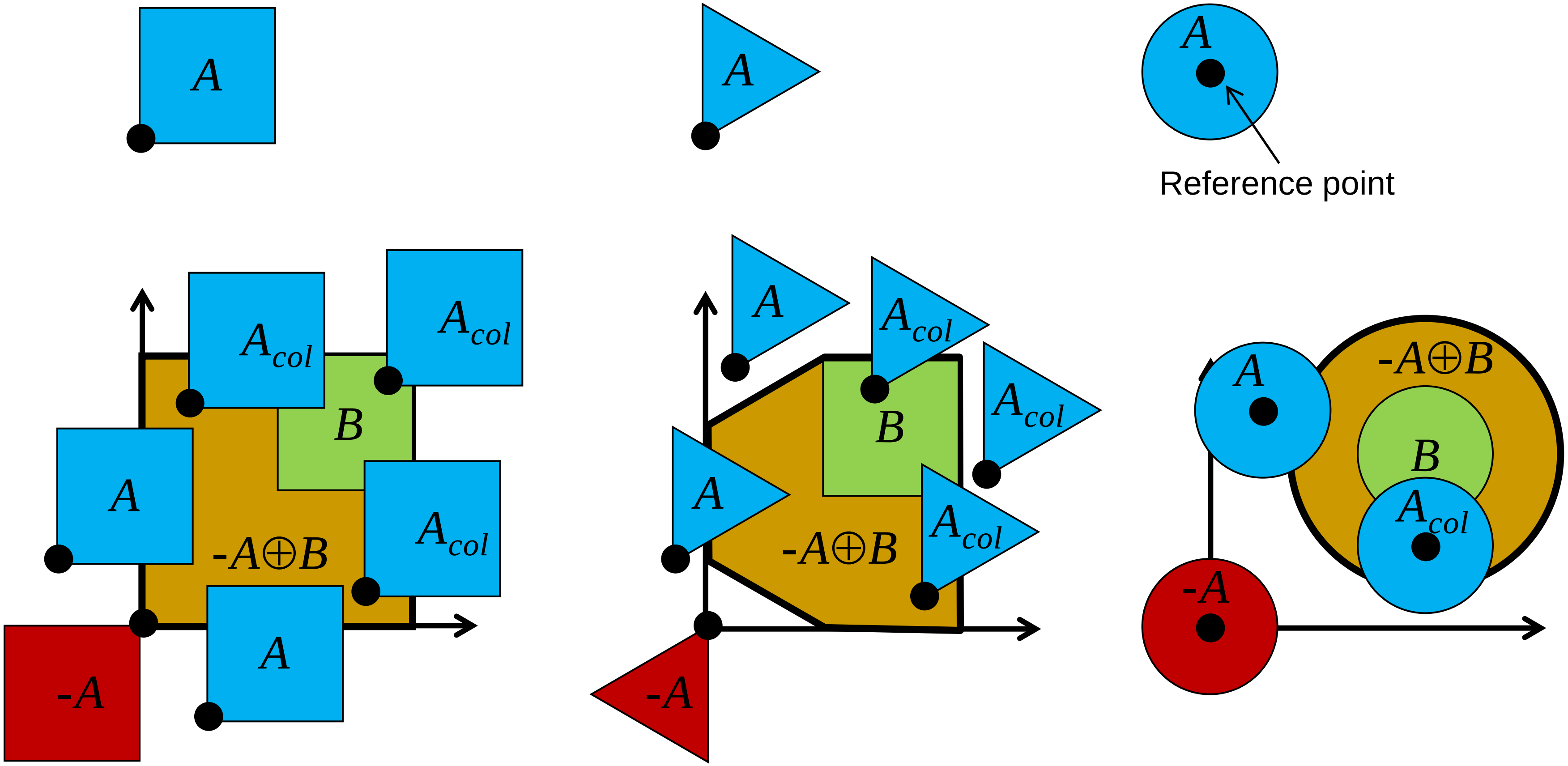
  Let $-A$ denote shape A reflected in its reference point: $-A = \{ -a \ / \ a \in A \}$

  -



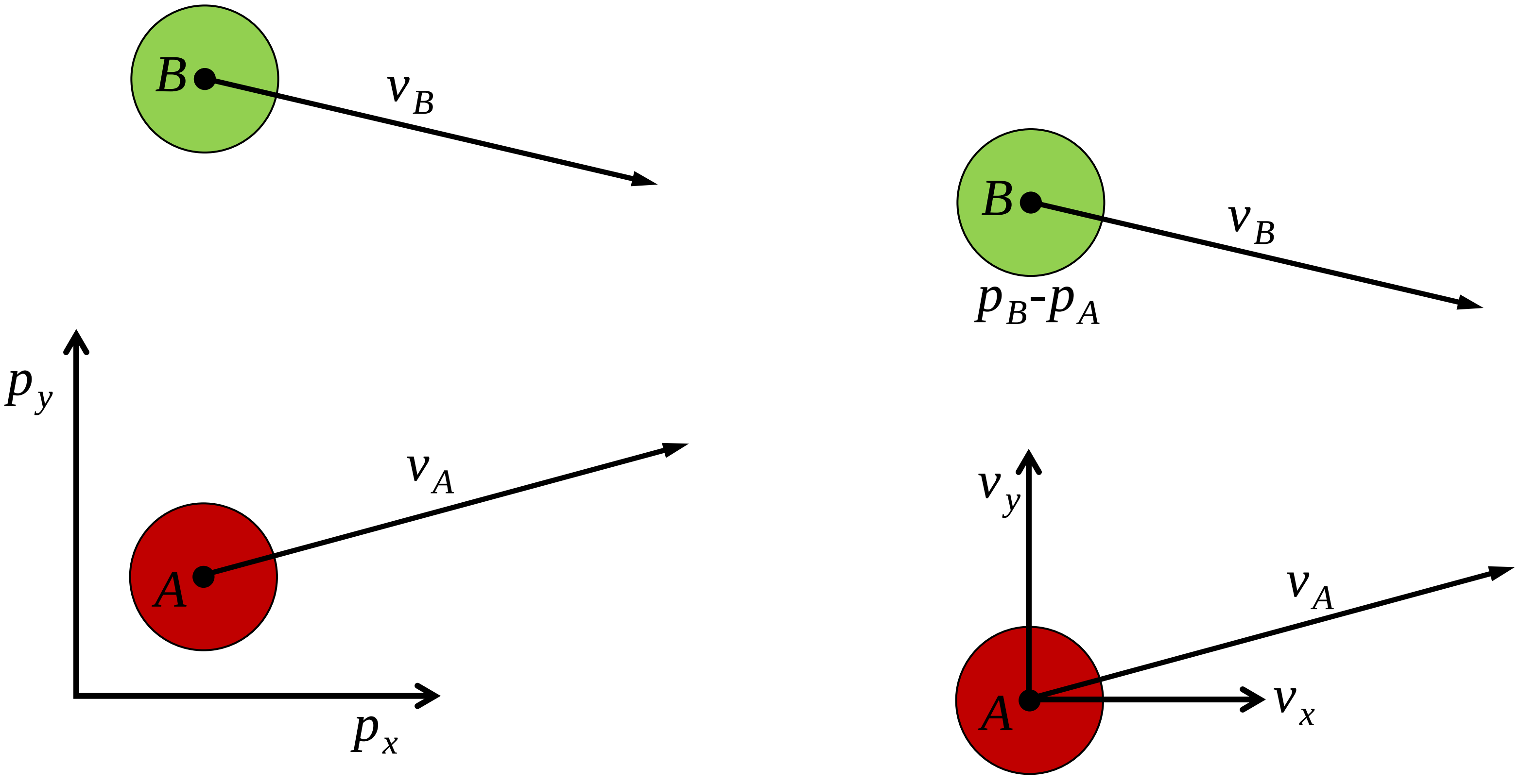
Velocity obstacle method

- Minkowski addition
  - Minkowski difference is related to image erosion
  - There is no collision if the reference point is outside the area $-A \oplus B$



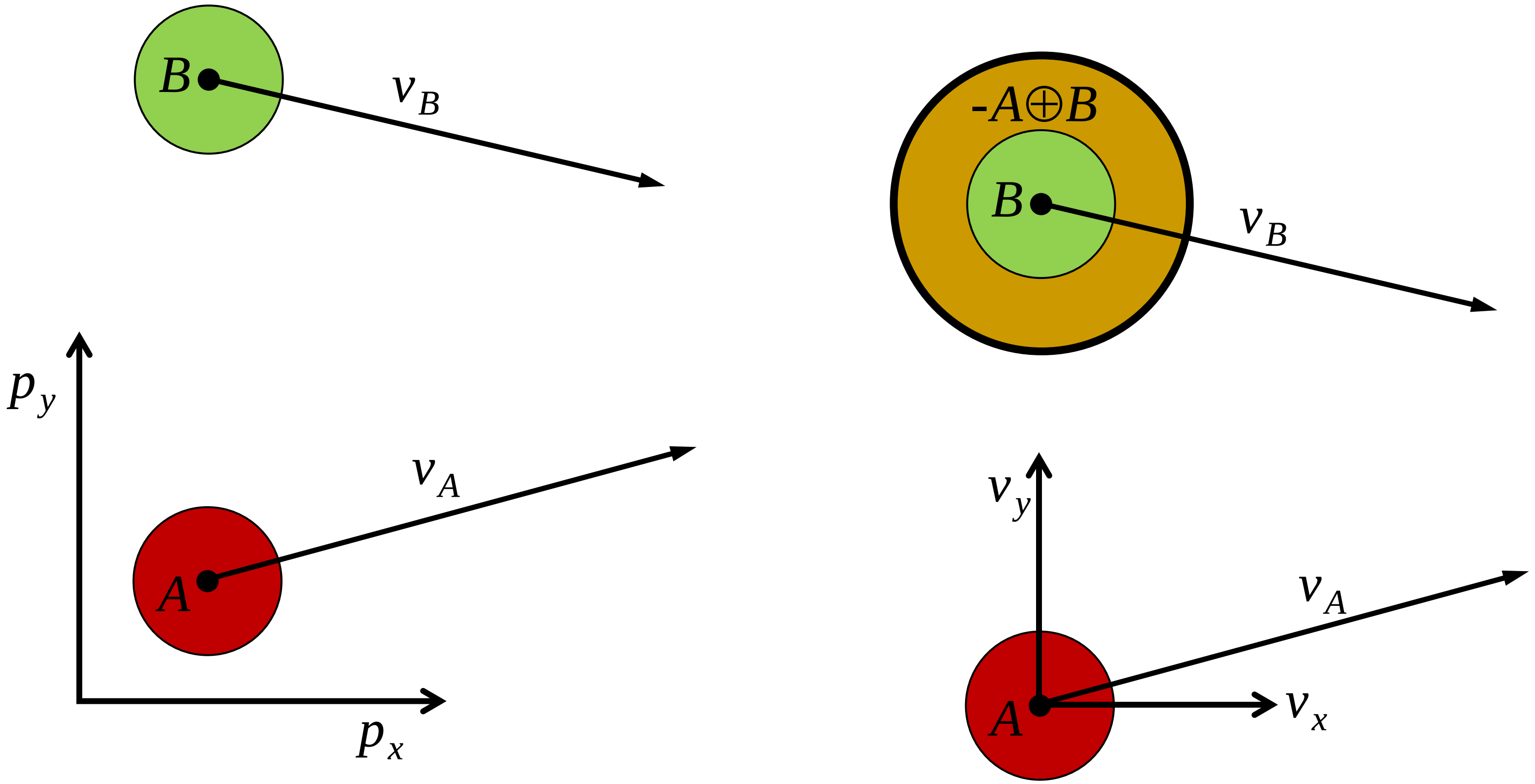
Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - Locate A at the origin of coordinates (p_A-p_A = 0) and B at (p_B-p_A)



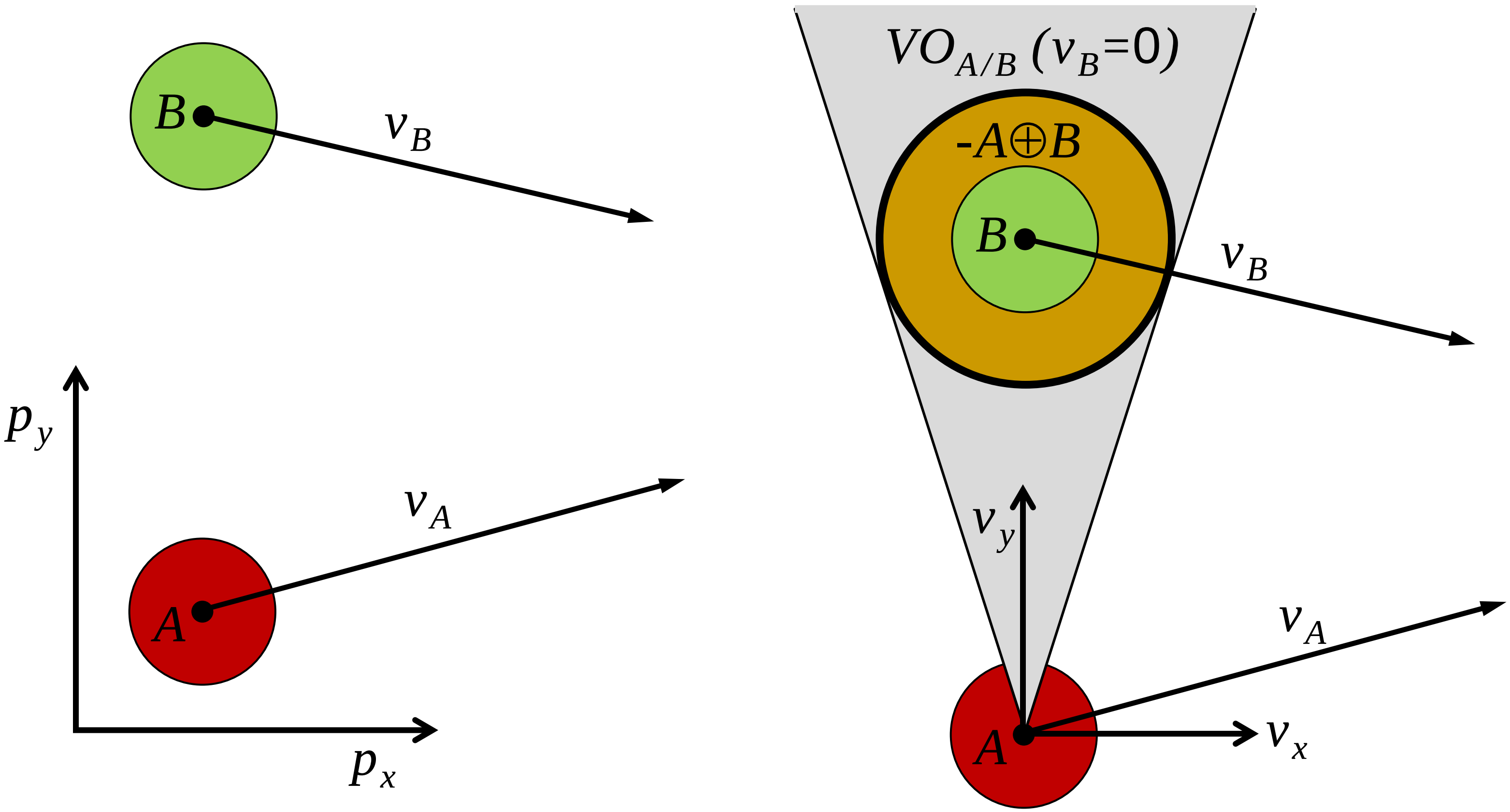
Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - Minkowski difference of coordinates (radius $r_A + r_B$)



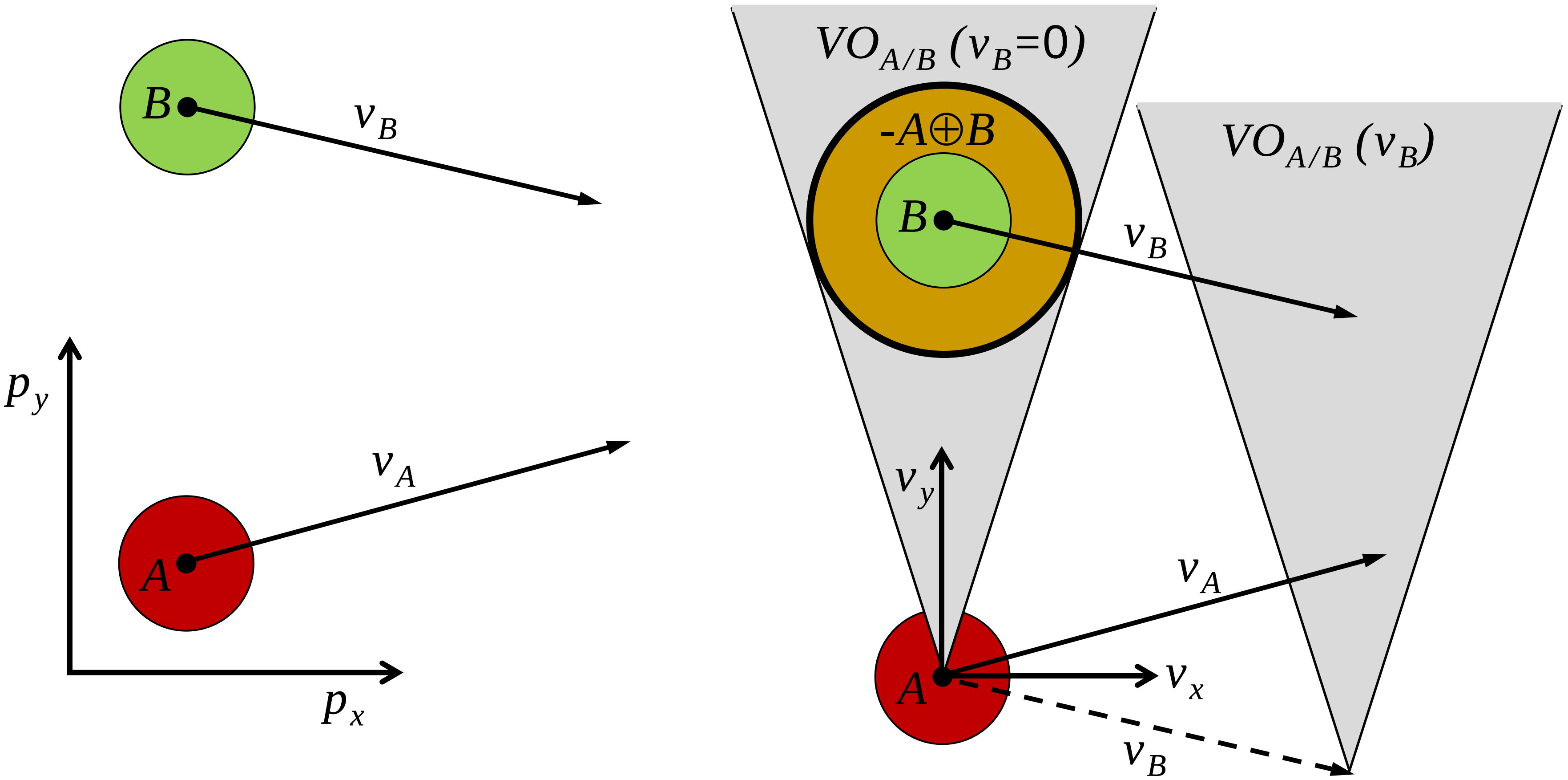
Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - Denote the velocity obstacle for robot A induced by dynamic obstacle B with $VO_{A/B}$



Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - Velocity obstacle $VO_{A/B}$ is the set of velocities of A that will result in collision with B in some time, assuming constant velocities



Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - Equivalence: if v_A lies in $VO_{A/B}$ (v_B) the relative velocity v_A-v_B lies in the velocity obstacle of B to A, assuming B does not move, i.e. $VO_{A/B}$ $(v_B=0)$

Let us denote $\lambda(p, v)$ a ray from p with direction v:

$\lambda(p, v) = \{p + t\, v \;/\; t \geq 0\}$

$VO_{A/B}(v_B) =$

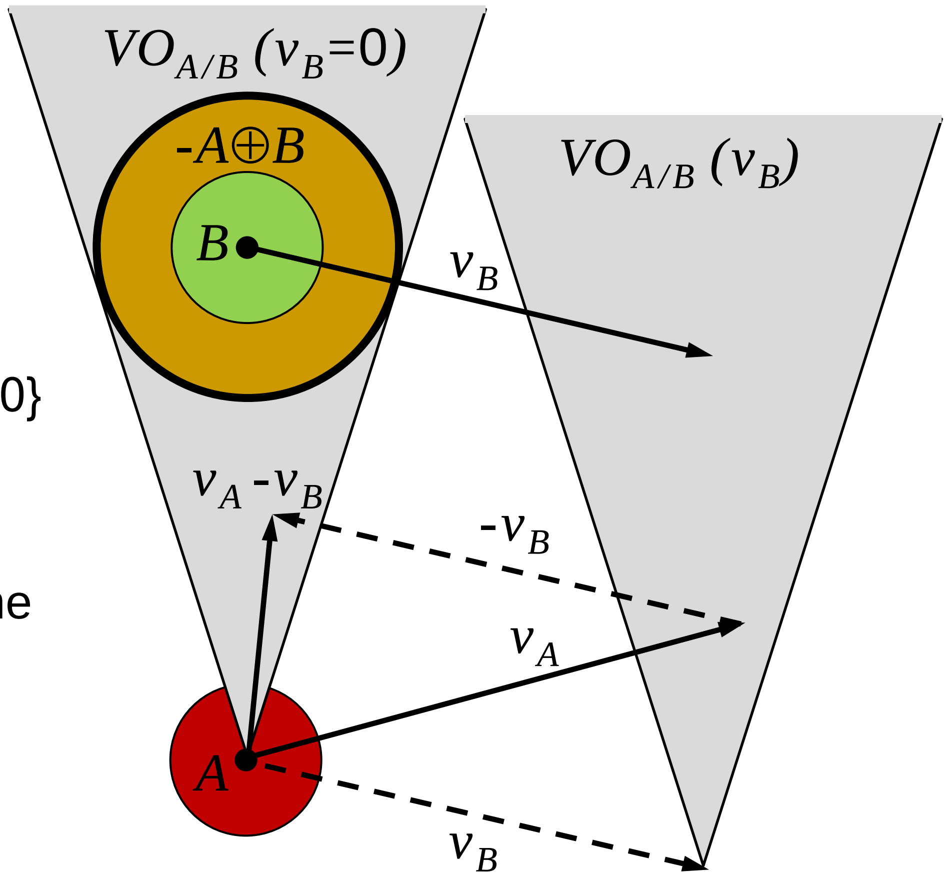
$$\{v_A \;/\; \lambda(p_A, v_A - v_B) \cap (-A \oplus B) \neq 0\}$$

Therefore, if $v_A \in VO_{A/B}(v_B)$

=> A and B will collide at some time

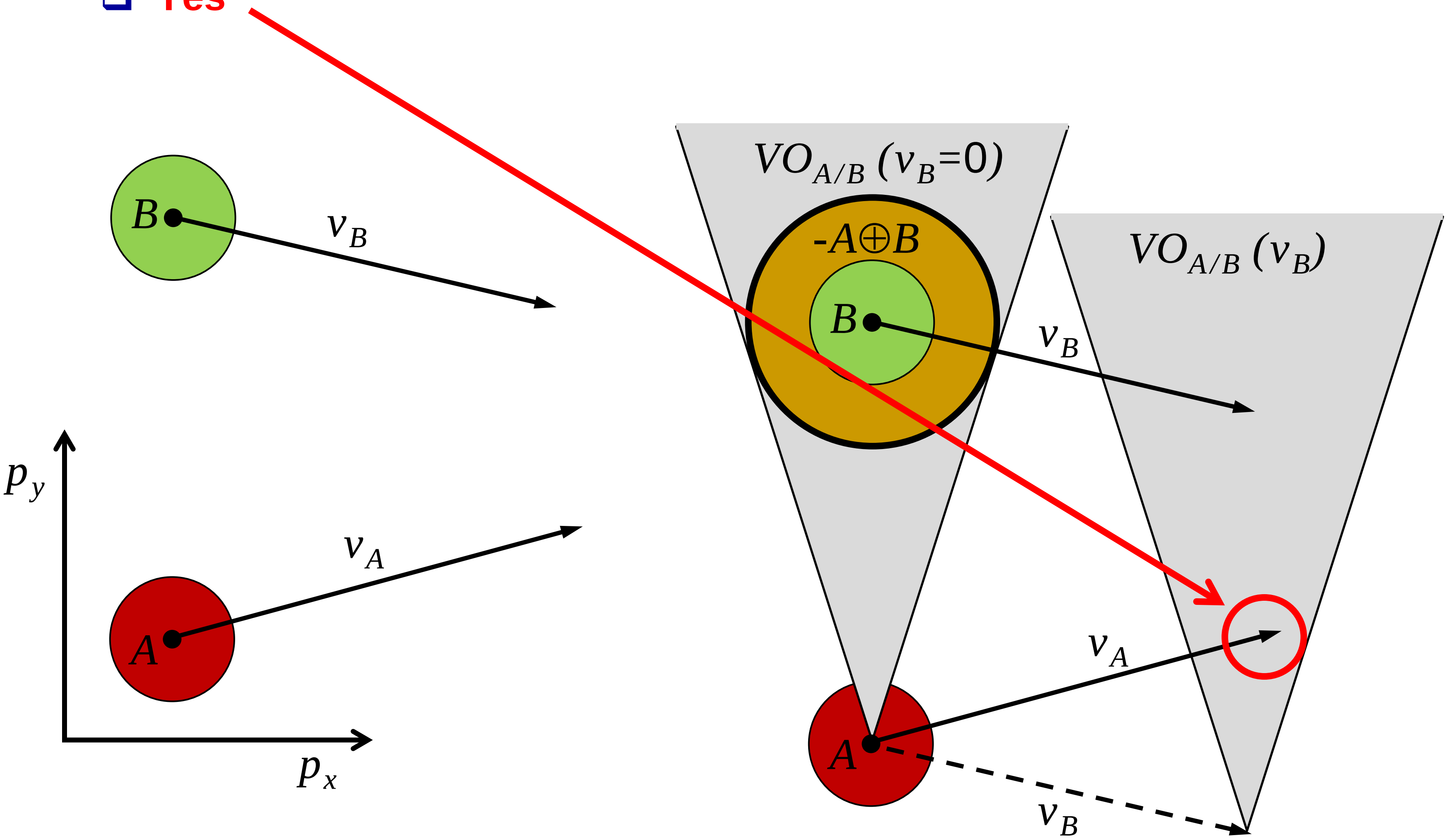
Otherwise, if $v_A \notin VO_{A/B}(v_B)$

=> A and B will never collide



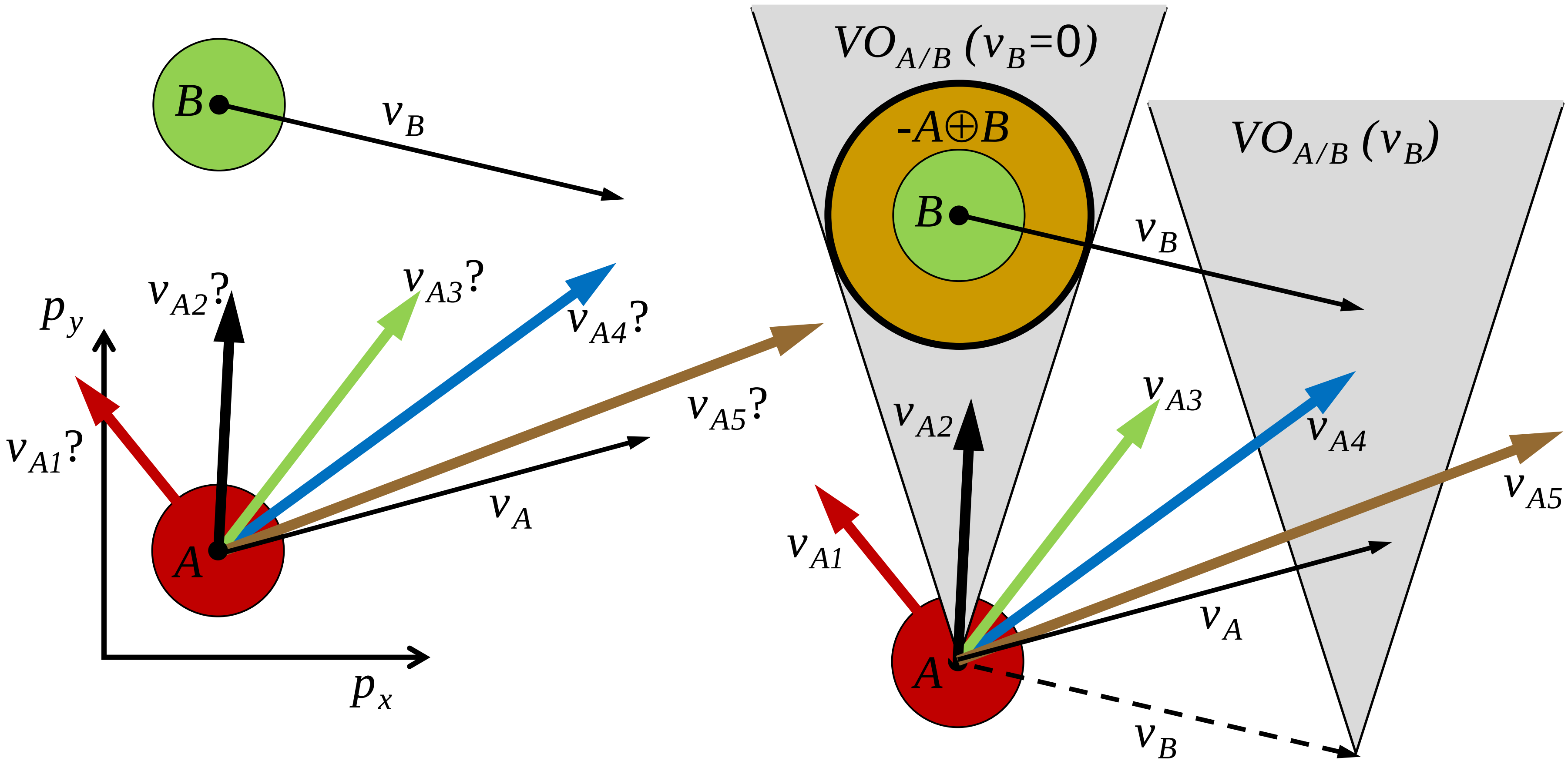
Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - **Yes**



Velocity obstacle method

- Given robots A and B moving in the plane, will they collide in ΔT?
  - In each step, choose a velocity v_A outside any of the velocity obstacles VO induced by the moving obstacles



Velocity obstacle method

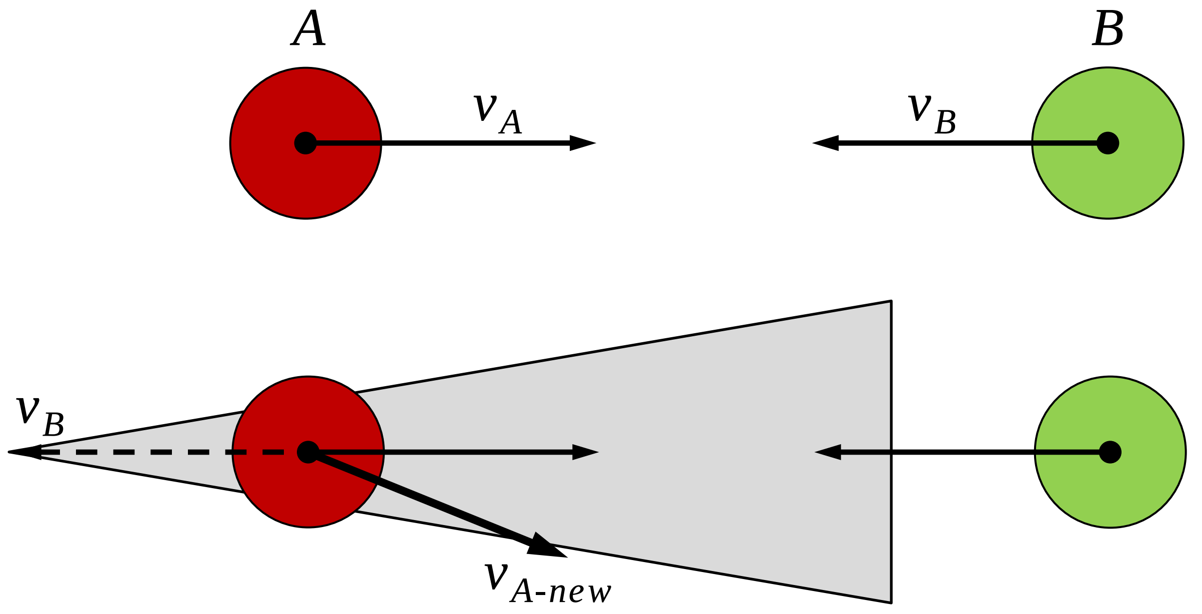
- Any strategy that selects velocities outside all *VO* will do
- Given a preferred velocity or a goal position, choose from all the free collision velocities the closest to them and the robot will reach safely the goal
- Drawbacks
  - In multirobot settings, the robots react when they perceive each other, adapting their motion. This should be taken into account
  - This may lead to undesired oscillations
  - There is also the problem of “reciprocal dances”. Although they may be common in natural human motion, they are undesirable for multi-robot navigation

Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method

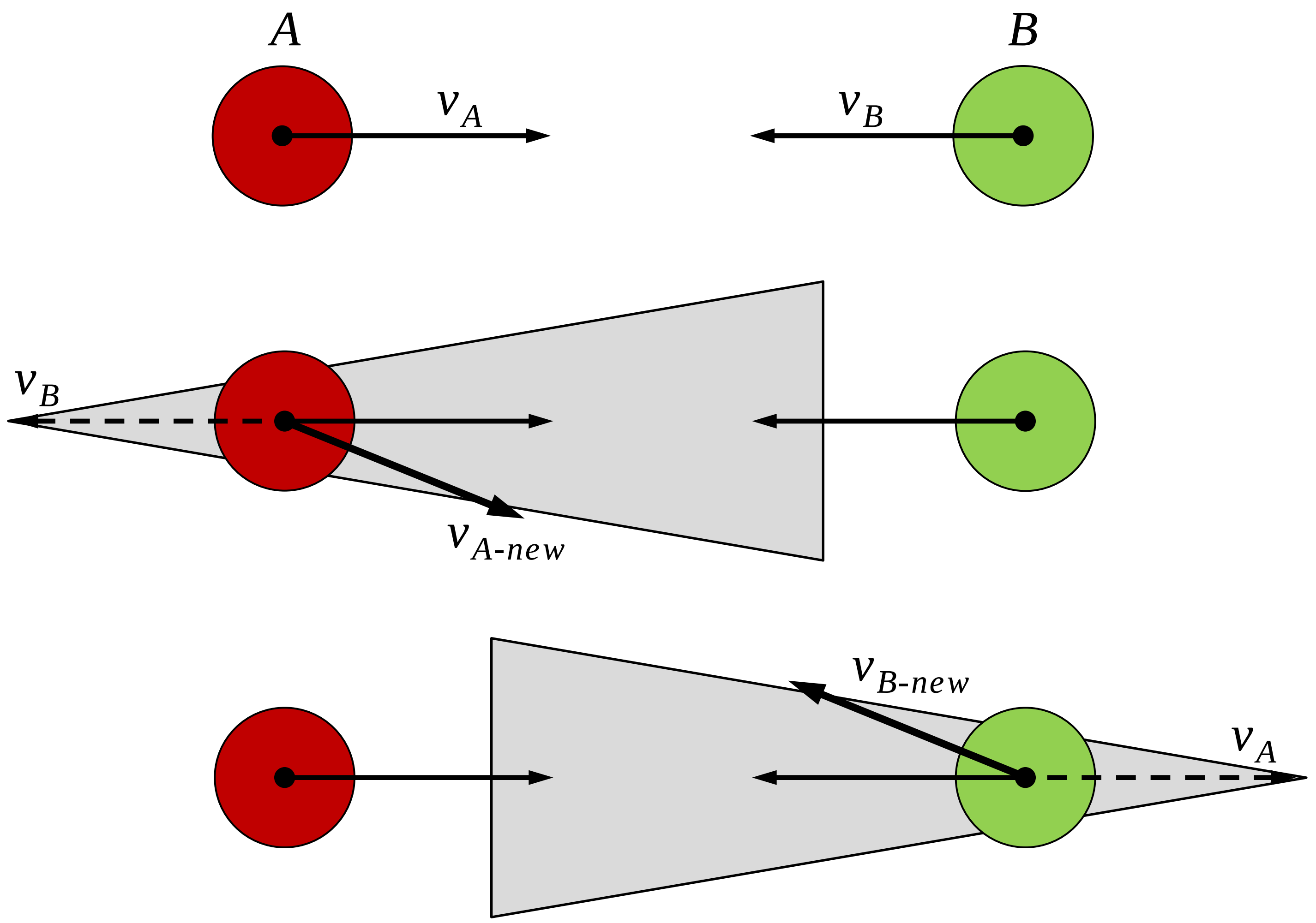
Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method



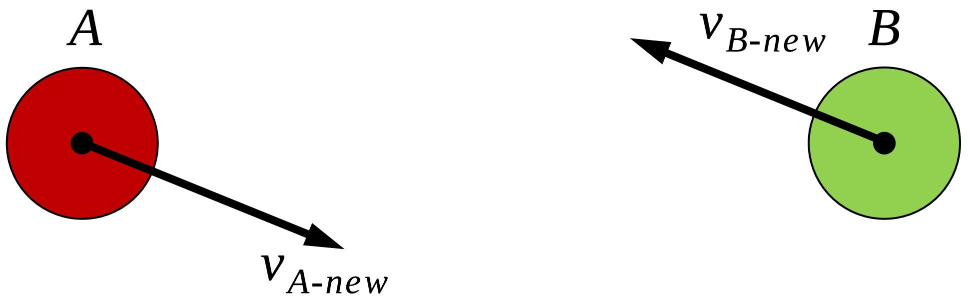
Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method



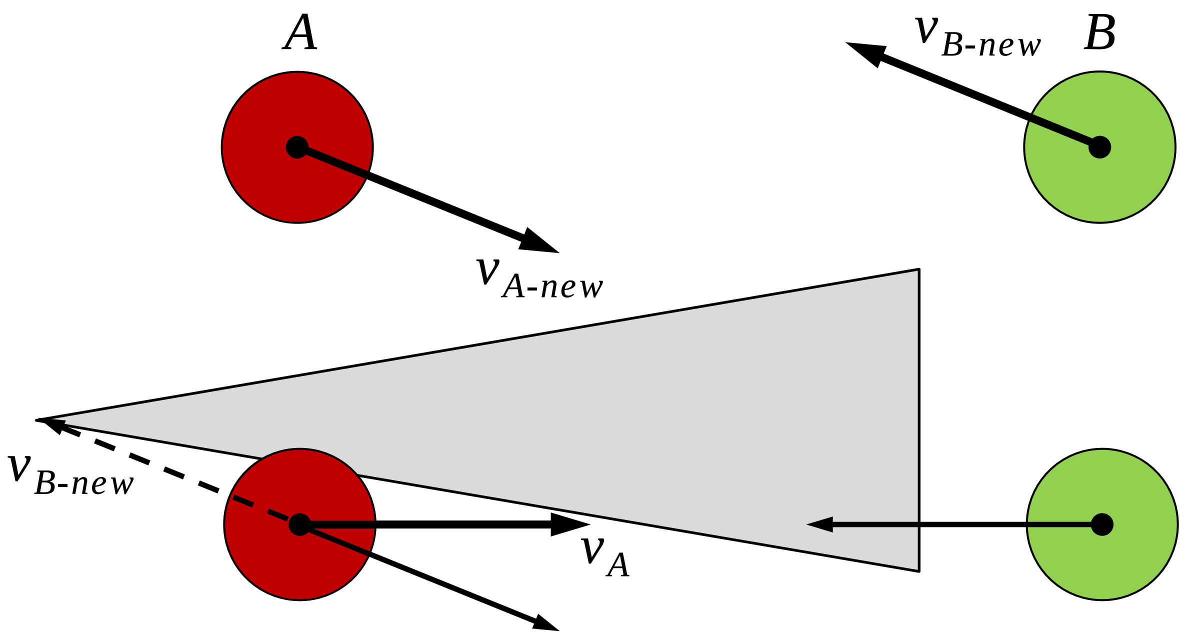
Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method



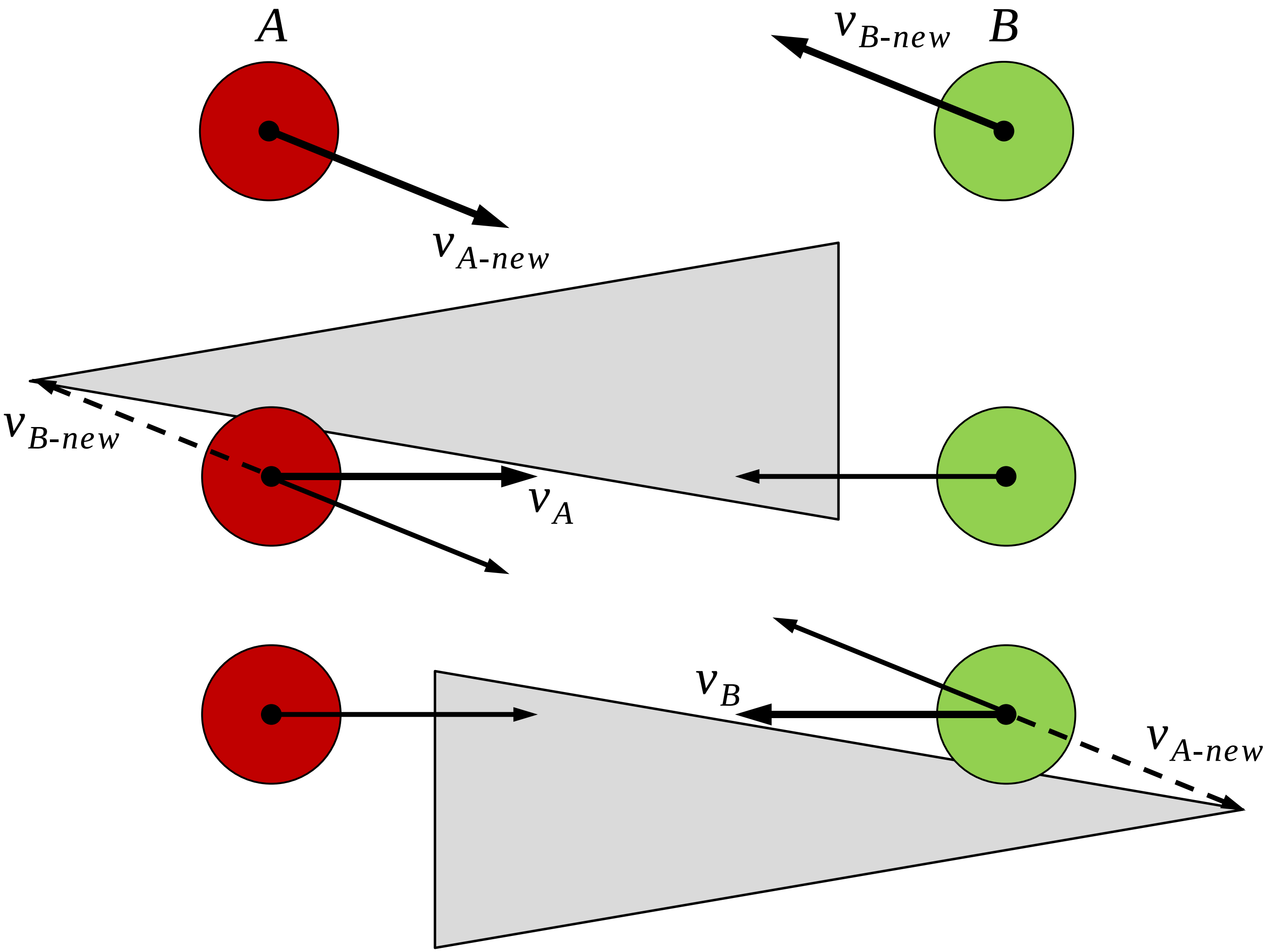
Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method



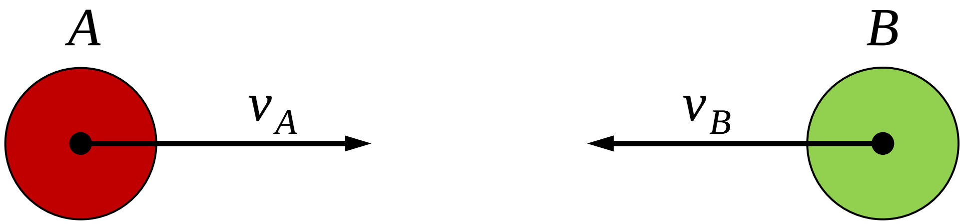
Reciprocal velocity obstacle method

- Oscillation problem of velocity obstacle method



Reciprocal velocity obstacle method

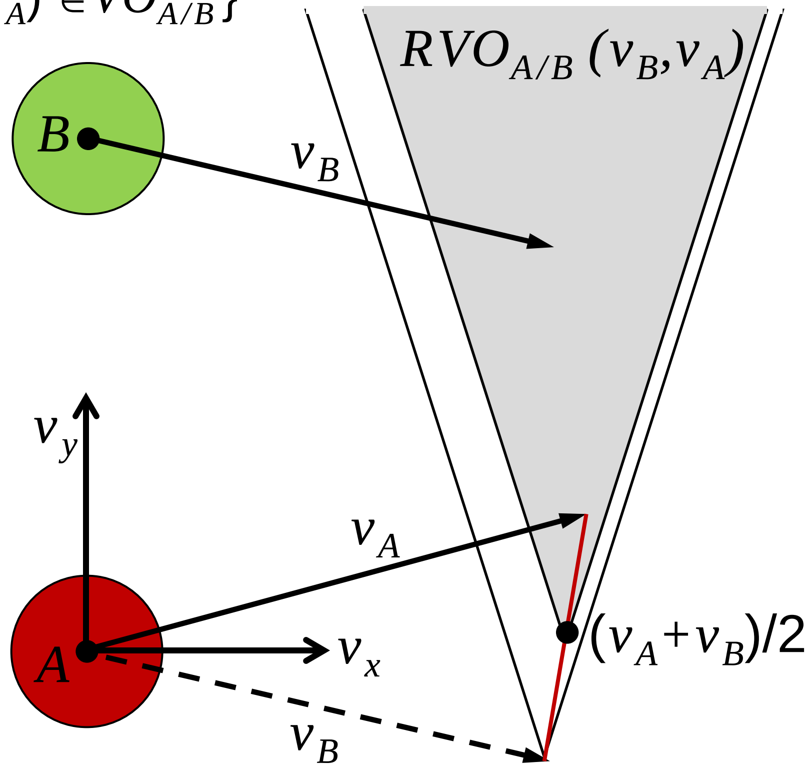
- Oscillation problem of velocity obstacle method



  - And history repeats itself…

Reciprocal velocity obstacle method

- The idea of the reciprocal velocity obstacle method (RVO) is:
  - Instead of choosing a new velocity for each agent that is outside the other agent's velocity obstacle,
  - we choose a new velocity that is the average of its current velocity and a velocity that lies outside the other agent's velocity obstacle.
  - $RVO_{A/B}(v_B, v_A) = \{ v$ such that $(2v - v_A) \in VO_{A/B} \}$

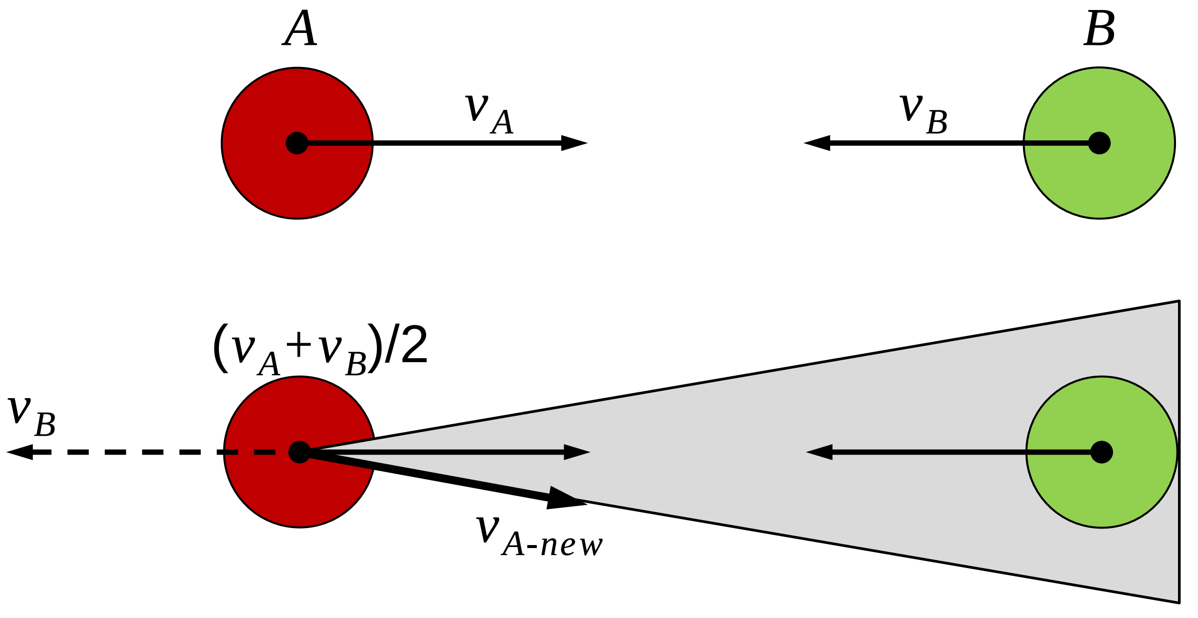


Reciprocal velocity obstacle method

- Let us check the oscillation problem

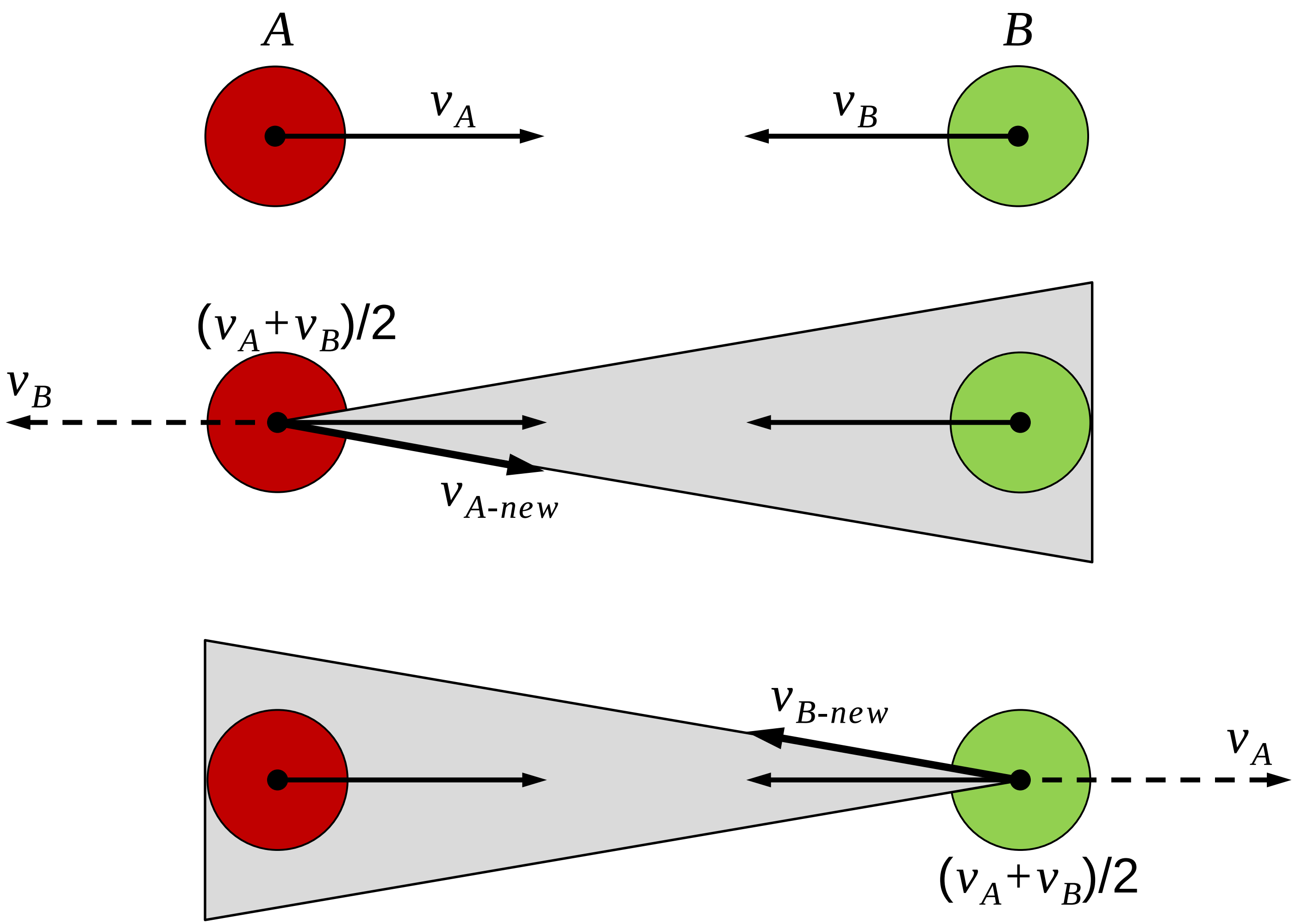
Reciprocal velocity obstacle method

- Let us check the oscillation problem



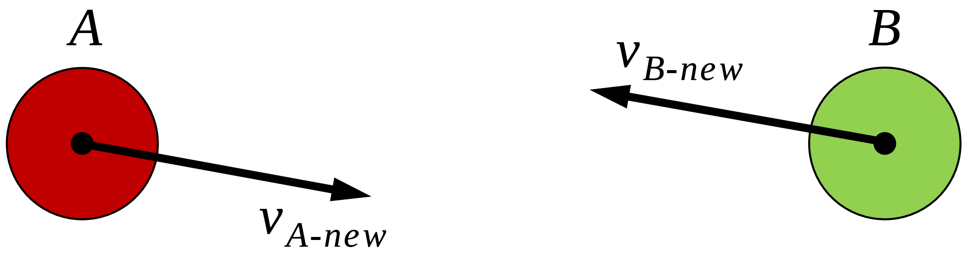
Reciprocal velocity obstacle method

- Let us check the oscillation problem



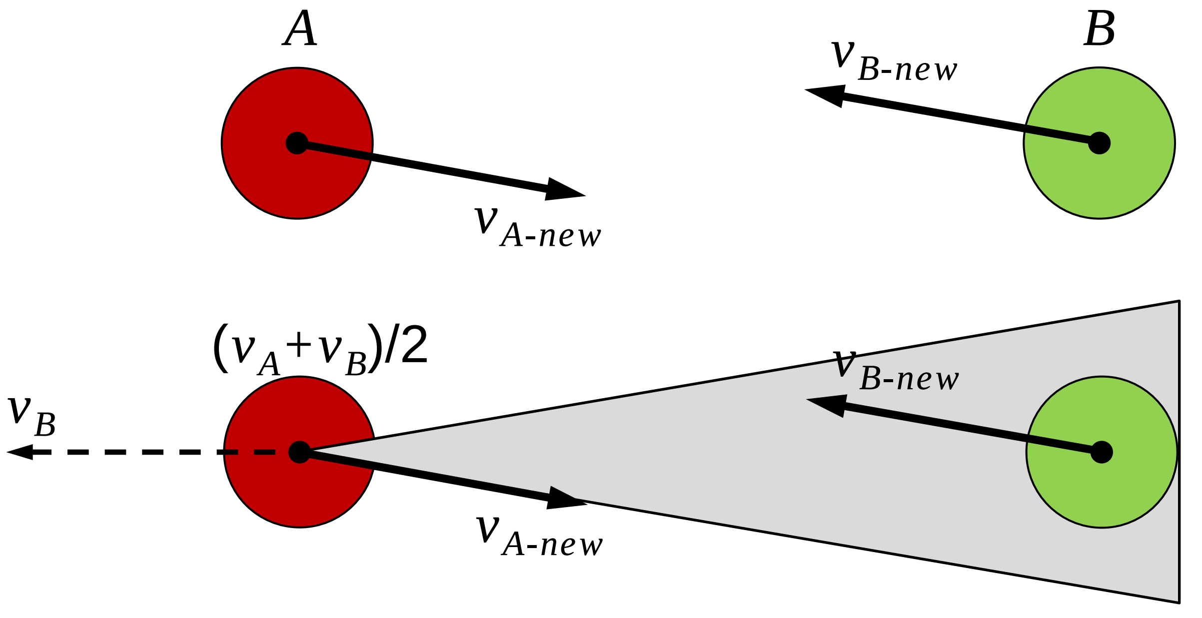
Reciprocal velocity obstacle method

- Let us check the oscillation problem



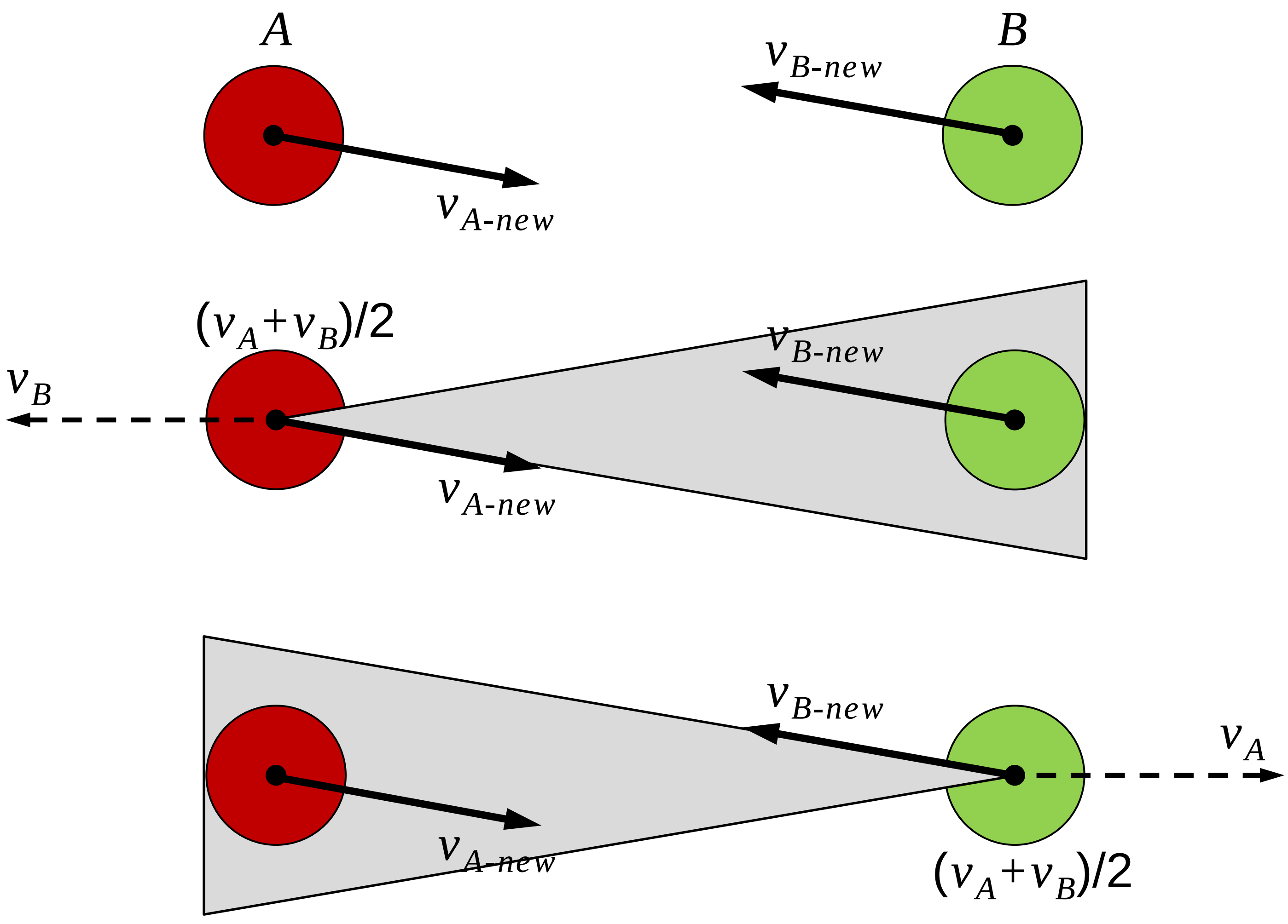
Reciprocal velocity obstacle method

- Let us check the oscillation problem



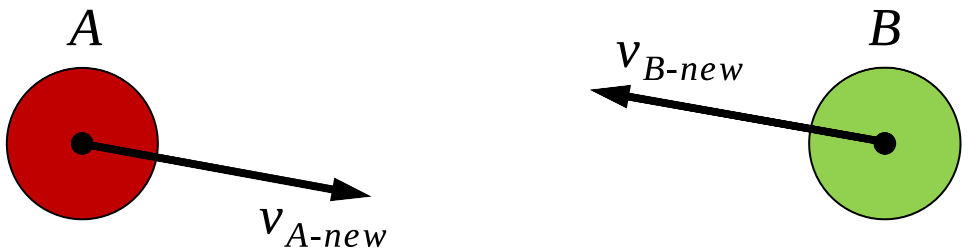
Reciprocal velocity obstacle method

- Let us check the oscillation problem

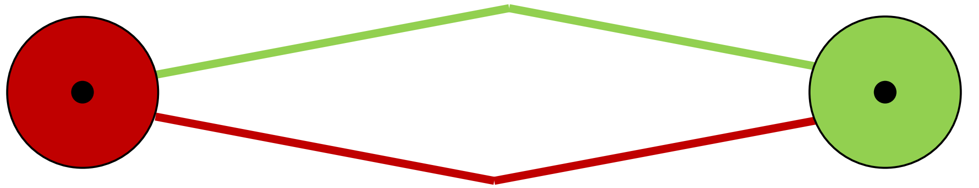


Reciprocal velocity obstacle method

- Let us check the oscillation problem

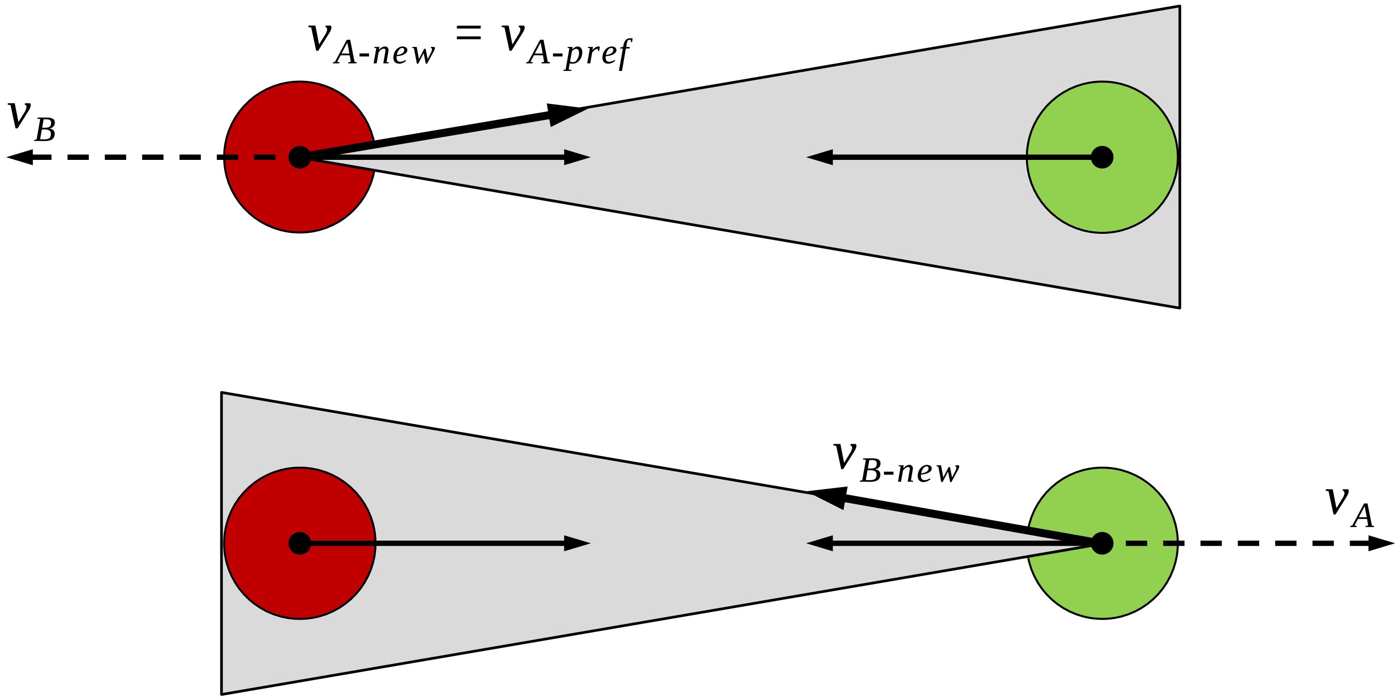


- Motion result:



Reciprocal velocity obstacle method

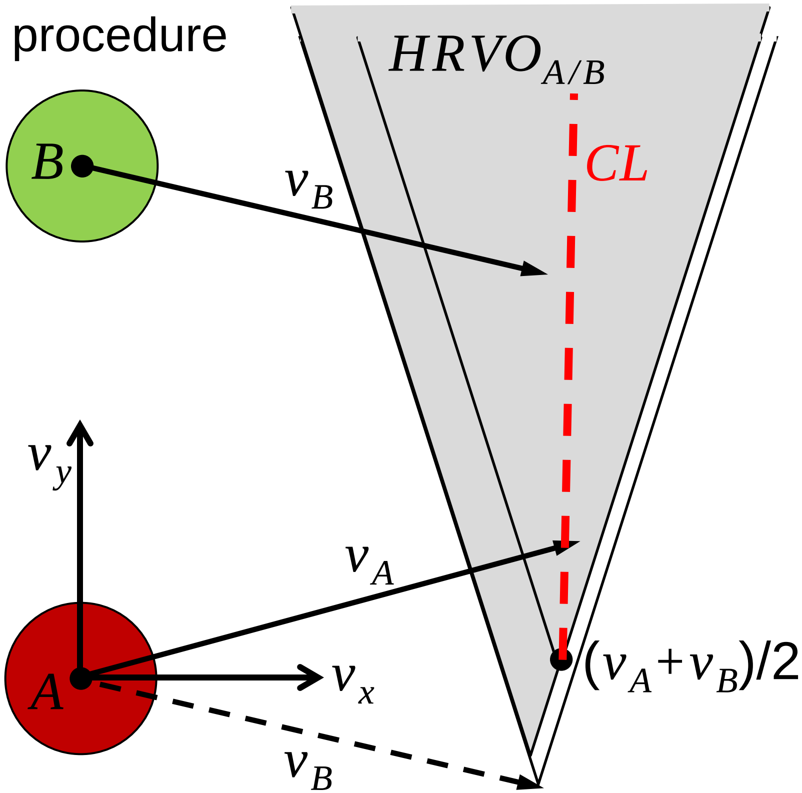
- However, rather that choosing the velocities closest to their current velocities, usually the robots are required to
  - follow a velocity closest to their preferred velocities,
  - A third robot may also cause to choose a v on the conflicting side



  - Therefore, the "reciprocal dances" still may happen

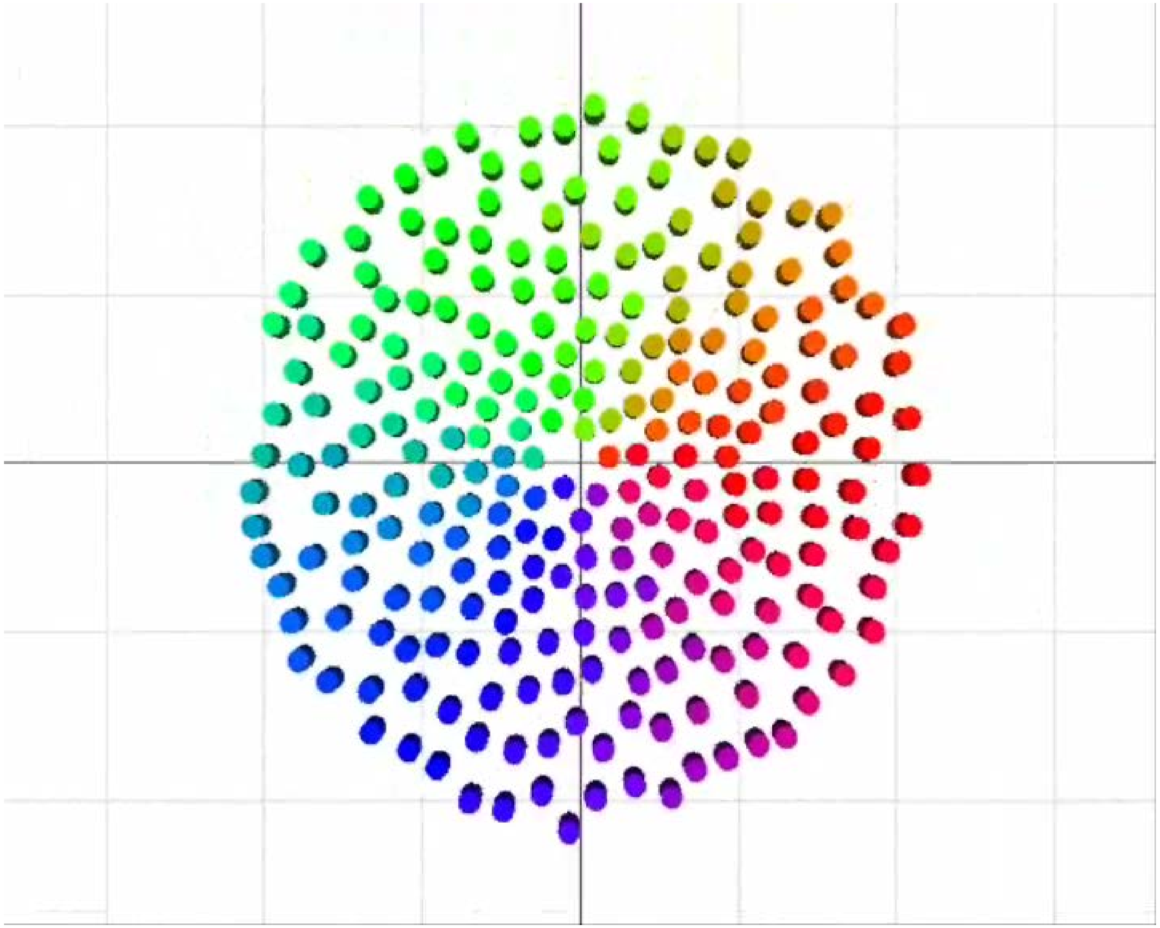
Hybrid reciprocal velocity obstacle method

- HRVO
  - We introduce the **Center Line** of $RVO_{A/B}$, CL:
  - If v_A is to the right of CL of $RVO_{A/B}$ (so v_B is to the right of CL of $RVO_{B/A}$) we want A to choose $v_{A\text{-}new}$ to the right of CL of $RVO_{A/B}$
  - The $RVO_{A/B}$ is enlarged on the left side => $HRVO_{A/B}$
  - If v_A is to the left of CL perform mirror procedure
  - This greatly reduces the possibility of oscillations



Hybrid reciprocal velocity obstacle method

- Examples



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