IDEC Seminar No.79/PHIS Seminar No.38, Hiroshima University

Toward Control Theory for Complex Systems: From Epidemics to Swarm and Weather

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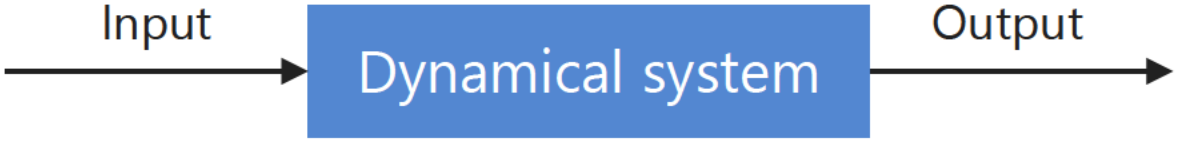
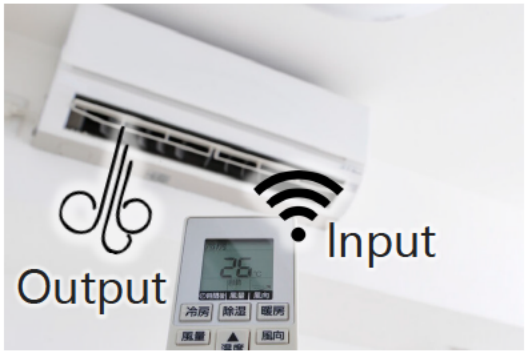
Control?

What is control?

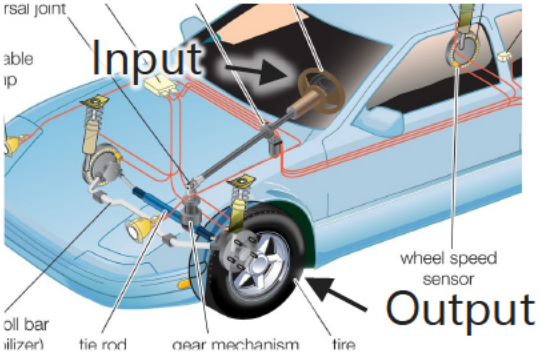
Adjusting input to obtain desired output from a dynamical system



Examples



Air conditioner
Use remote to achieve desired air temperature



Car driving
Steer handle to achieve desired direction

Pitching
Throw ball to reach desired position at desired speed

Control technology

$1.5 million /year/plant

20,000 robots

10 years

Fault detection

>6 control loops /phone

200,000 patients

Billions of suspensions

Samad et al,. "Industry engagement with control research: Perspective and messages", *Annual Reviews in Control*, 2020

Control engineering

Engineering discipline focusing on:

Controller design for realizing desired system behavior

Paradigm: feedback control

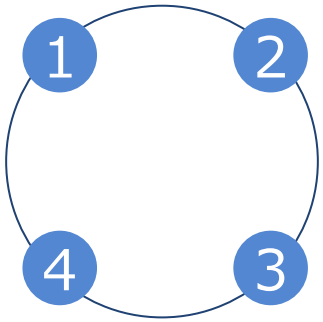
Control research

Identifying real-world challenges

- Recognize key societal issues to define control problems

Formulating the problem

- Build a simple model to capture the essence of the control problem



Proposing control theory and/or algorithms

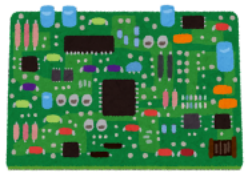
- Propose solutions based on mathematical analysis and simulations

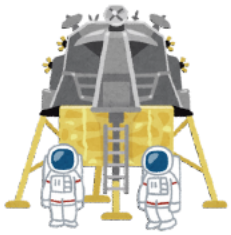
Conducting evaluation

- Assess the scope of proposed solutions and apply them in practice

Control applications

"Ashton Frost engine at Mill Meece Pumping Station," Globbet, licensed under CC BY-SA 3.0





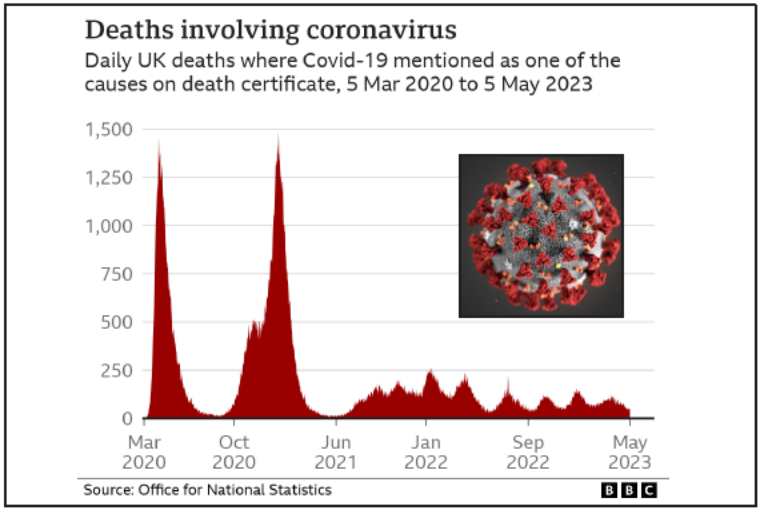
? ? ?

1800

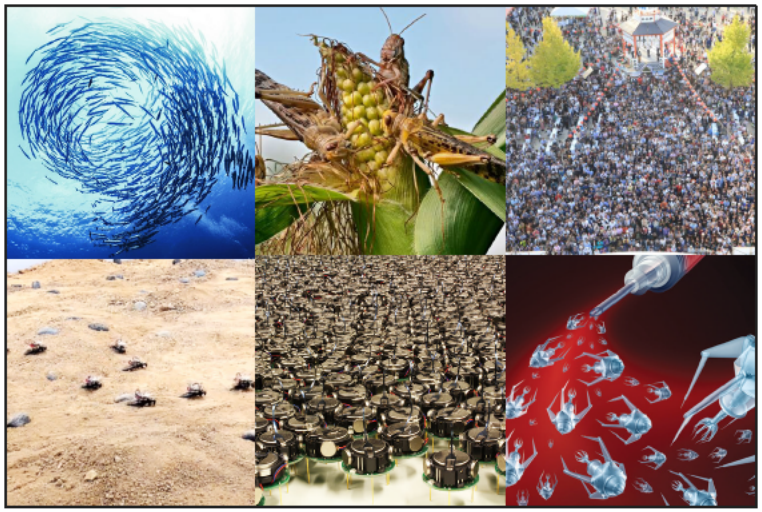
2000

2100

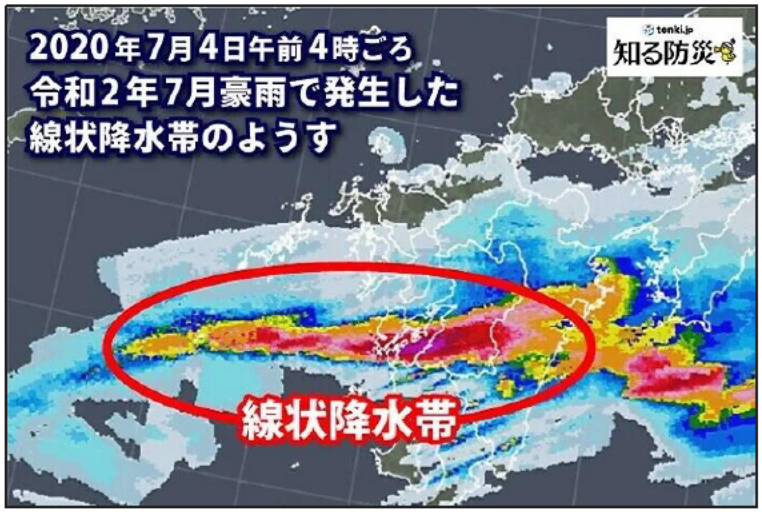
Open areas



Epidemics



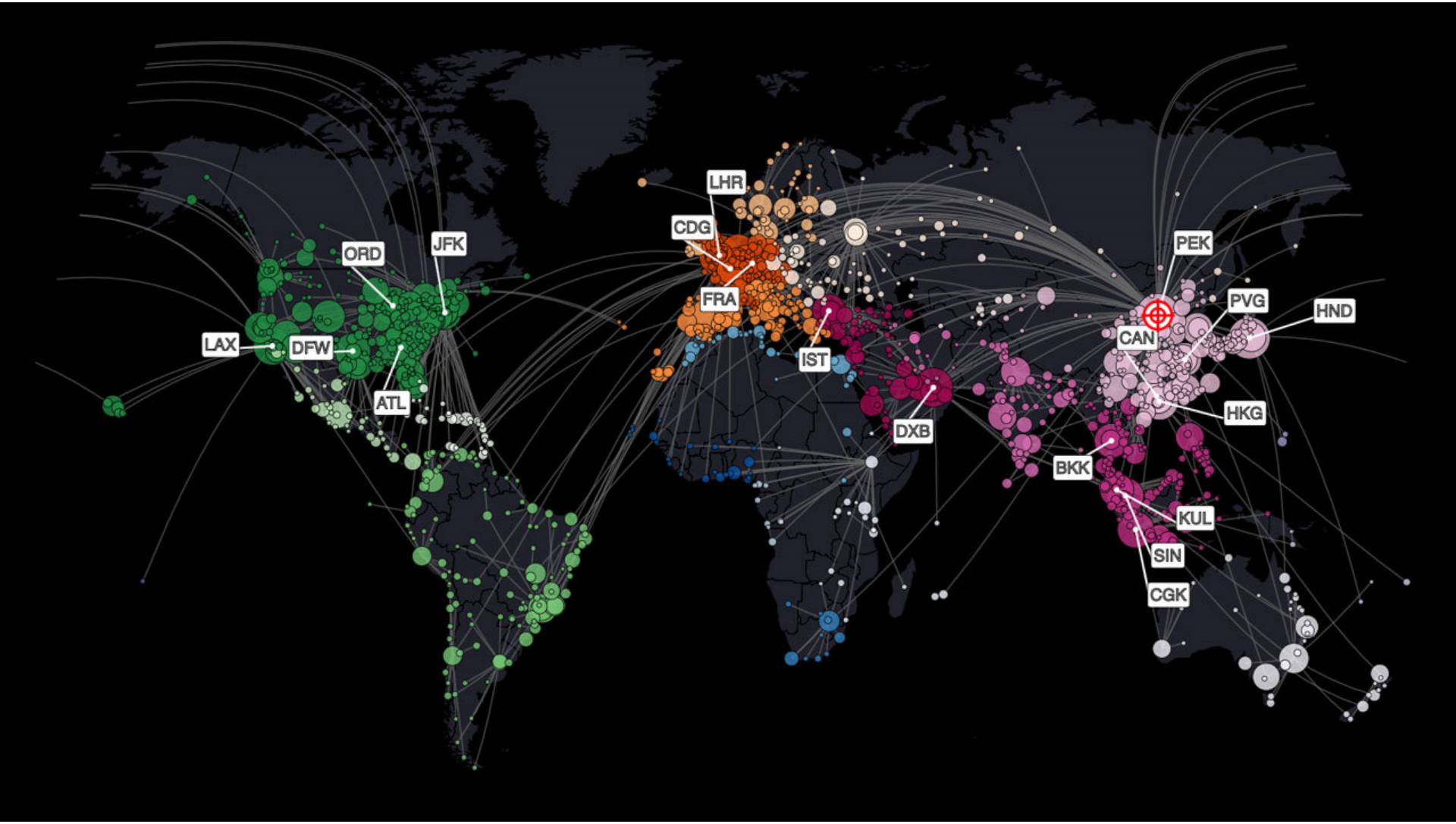
Swarms



Weather

Epidemics

COVID-19 pandemic

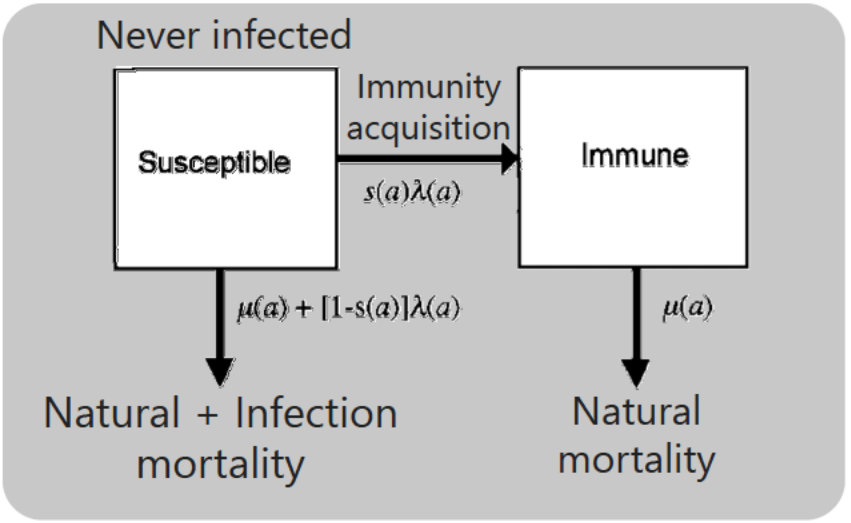


https://www.science.org/content/article/scientists-are-racing-model-next-moves-coronavirus-thats-still-hard-predict

Early research

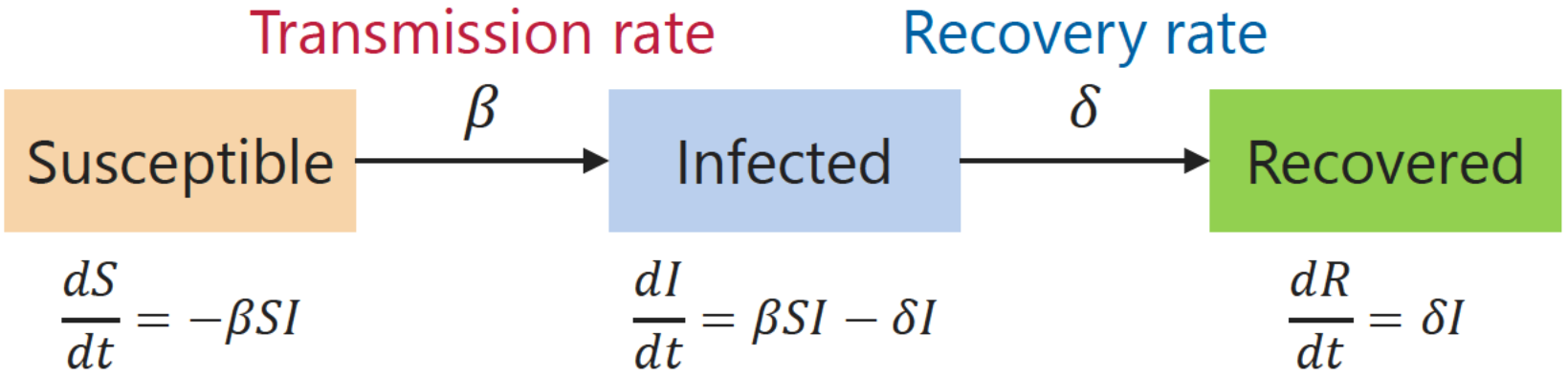
- Smallpox epidemics in 18th century Europe
  - Mortality rate 20-60%
  - Annual deaths: approximately 400,000
- Variolation
  - Effective but associated with a fatality rate of 0.5%
  - Public dilemma: Should one undergo variolation?
- Two-compartmental model (Daniel Bernoulli)
  - Mathematical analysis of impact of variolation
  - Conclusion: Variolation increases life expectancy if its fatality rate is below 11%.

Lady Mary Wortley Montagu



Colombo, Diamanti, "The smallpox vaccine: the dispute between Bernoulli and d'Alembert and the calculus of probabilities," *Lettera Matematica*, 2015.

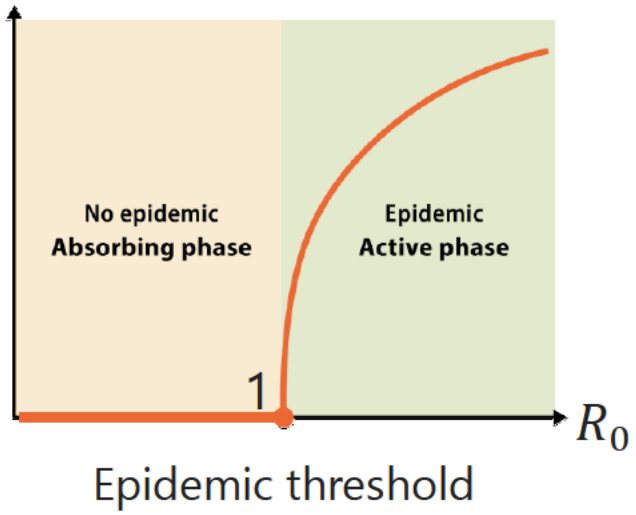
A modern treatment: SIR model



- Basic reproduction number

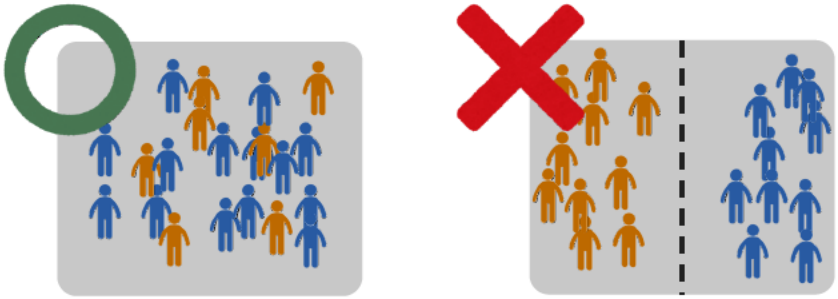
$$R_0 = \beta/\delta$$

infected



Epidemic threshold

- Well-mixed assumption: accuracy of the model is based on assumption that two compartments are well-mixed.

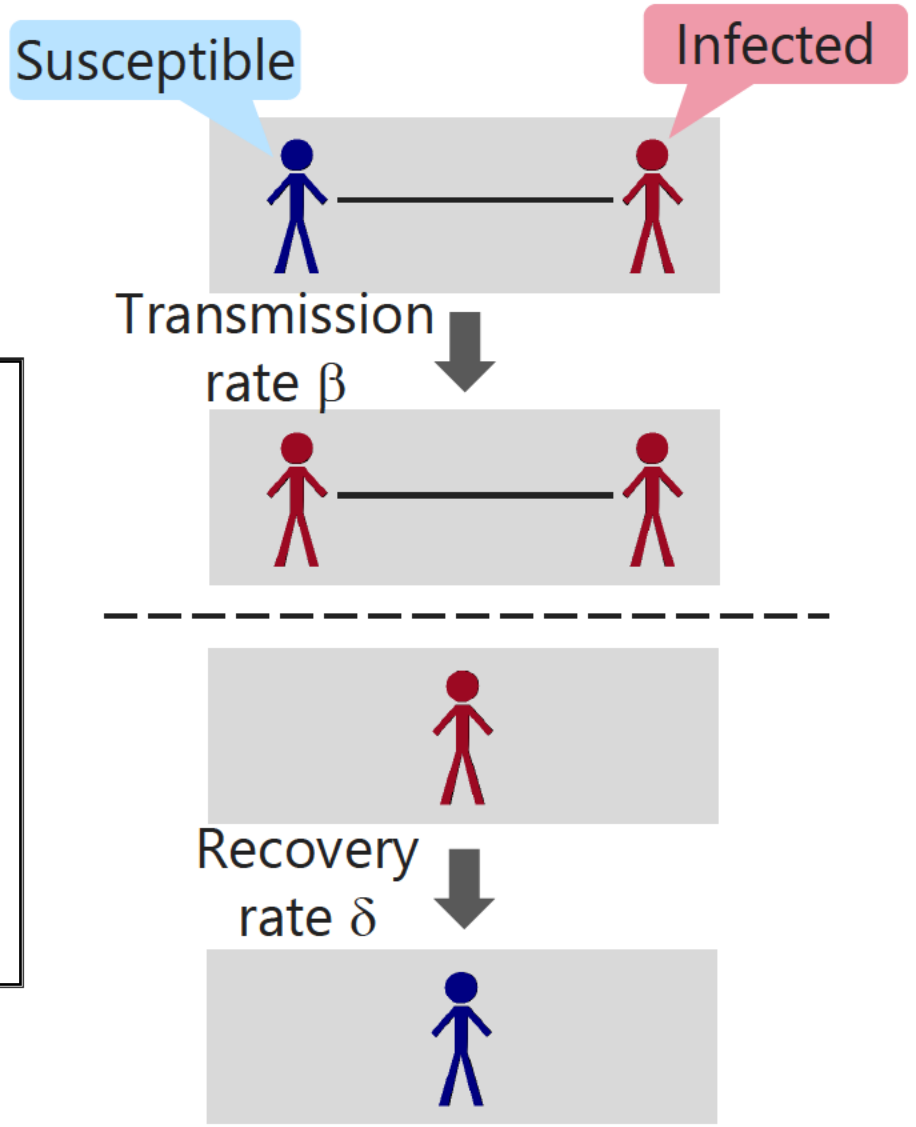


Not necessarily true in reality

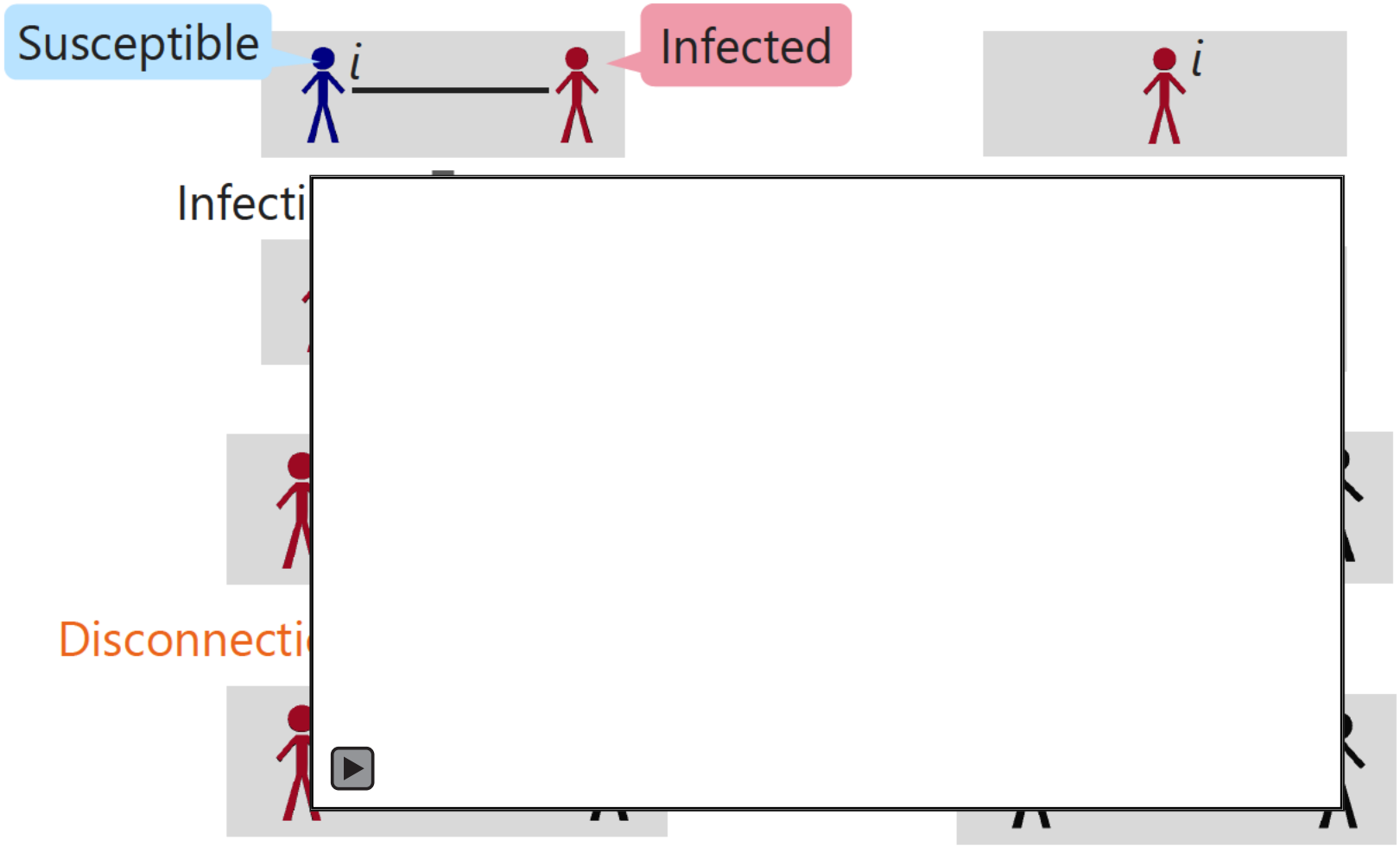
Networked SIS model

Stochastic model on networks

- Node = individual
- Edge = relationship



Adaptive SIS model

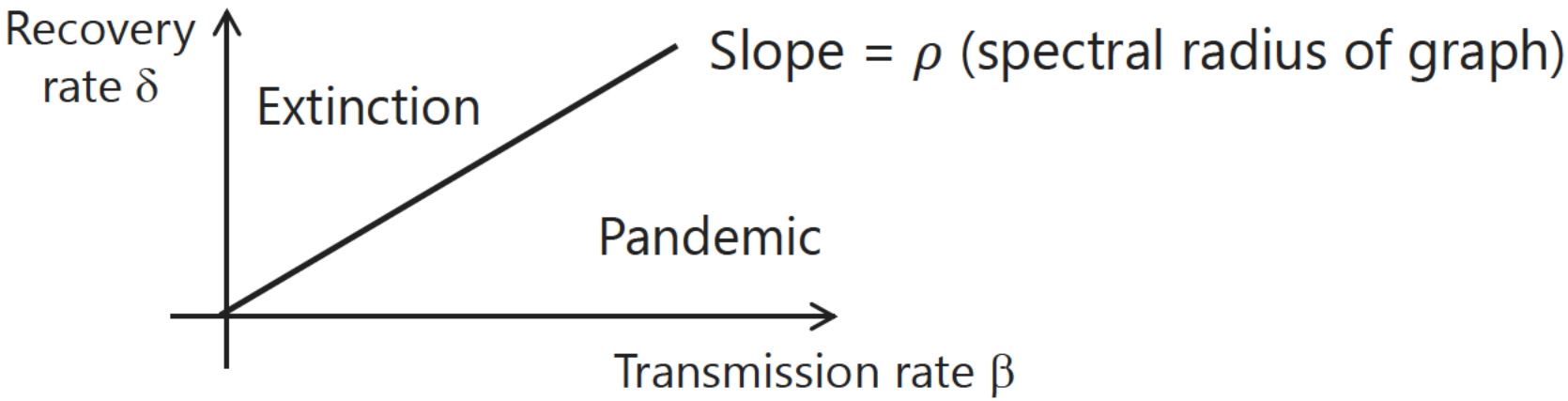


Not clear how large disconnection rate ϕ is necessary

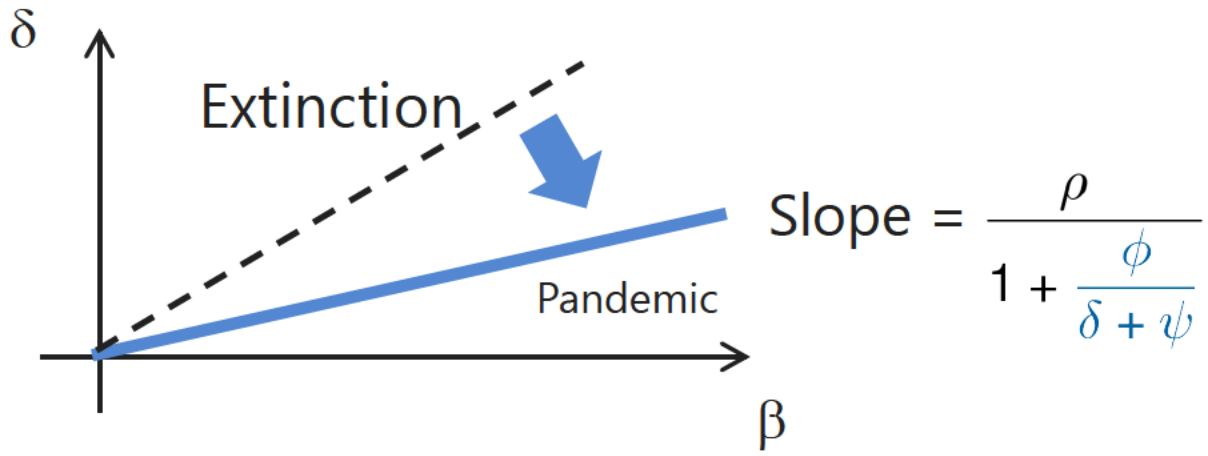
Guo et a
epidemics in adaptive networks," *Physical Review E*, 2013.

Asymptotic analysis

- Networked SIS model



- Adaptive SIS model



Ogura, Preciado, "Epidemic processes over adaptive state-dependent networks," *Physical Review E*, 2016.

Transformation into Poisson SDE

ASIS model = Markov process w/ exponentially many states

- Computationally intractable

SDE representation

- Nodal states $x_i \in \{0, 1\}$

$$dx_i(t) = -x_i(t)dN_{\delta_i}(t) + (1 - x_i(t)) \sum_{k \in \mathcal{N}_i(0)} a_{ik}(t)x_k(t)dN_{\beta_i}(t)$$

- Edge states $a_{ij} \in \{0, 1\}$

$$da_{ij}(t) = (1 - a_{ij}(t))dN_{\psi_{ij}}(t) - a_{ij}(t)\left(x_i(t)dN_{\phi_{ij}}(t) + x_j(t)dN_{\phi_{ji}}(t)\right)$$

Upper-bound for expectations $p_i(t) = E[x_i(t)]$ $q_{ij}(t) = E[a_{ij}(t)x_i(t)]$

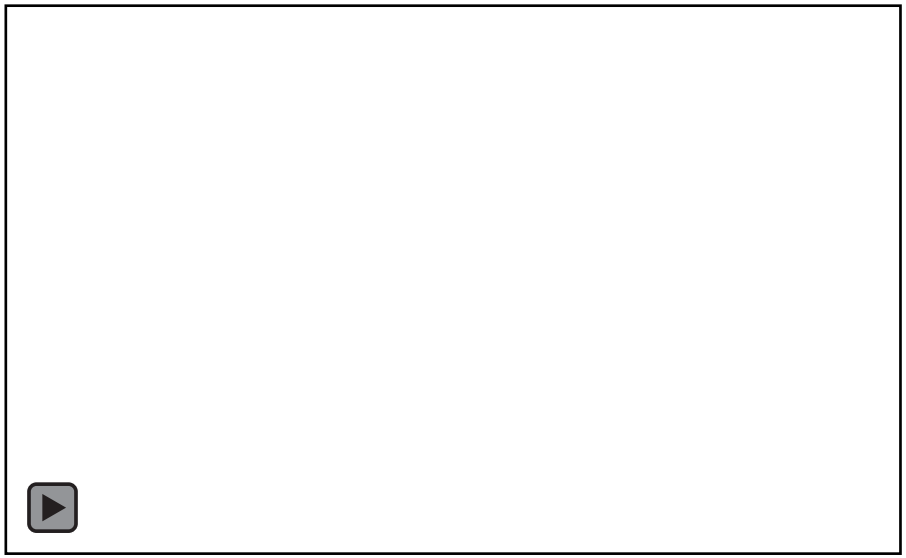
$$\frac{dp_i}{dt} = -\delta_i p_i + \beta_i \sum_{k \in \mathcal{N}_i(0)} q_{ki}$$

$$\frac{dq_{ij}}{dt} \leq -\phi_{ij}q_{ij} + \psi_{ij}(p_i - q_{ij}) - \delta_i q_{ij} + \beta_i \sum_{k \in \mathcal{N}_i(0)} q_{ki}$$

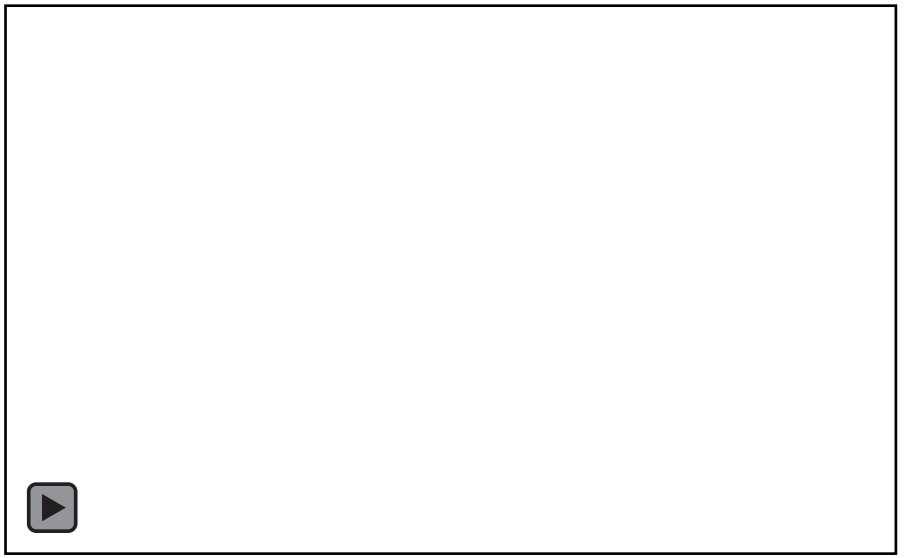
Simulation

- Karate network
- Homogeneous rates of transmission, recovery, and reconnection
- Critical disconnection rate ϕ^*

Less frequent disconnection ($\phi = \phi^*/10$)



More frequent disconnection ($\phi = 2\phi^*$)



Optimal distancing strategy

Disease eradication ⟷ Trade-off ⟷ Keeping societal functions

- Question:

  How can we tune adaptation rates to eradicate spreading processes while minimizing societal loss?

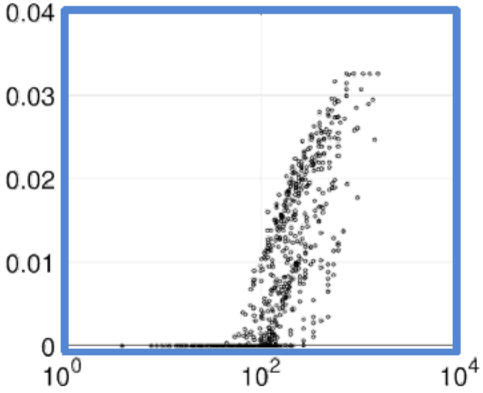
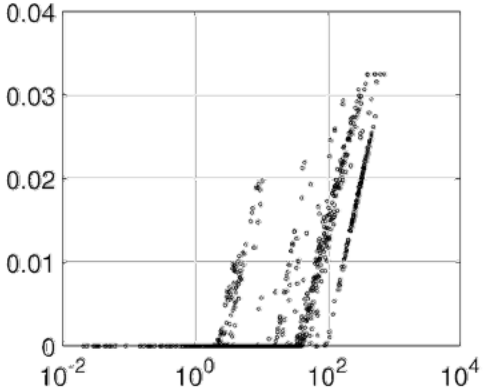
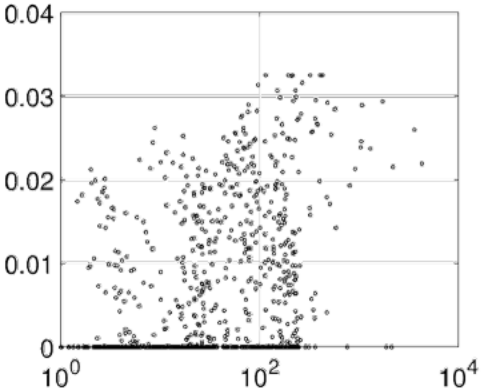
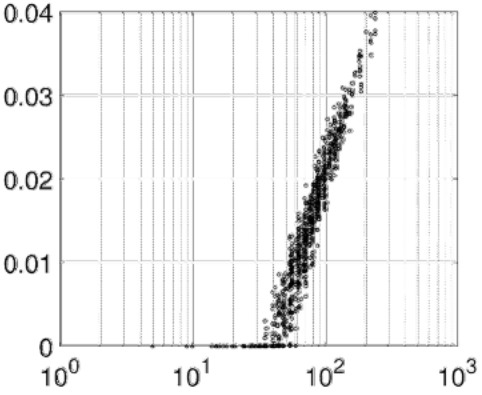
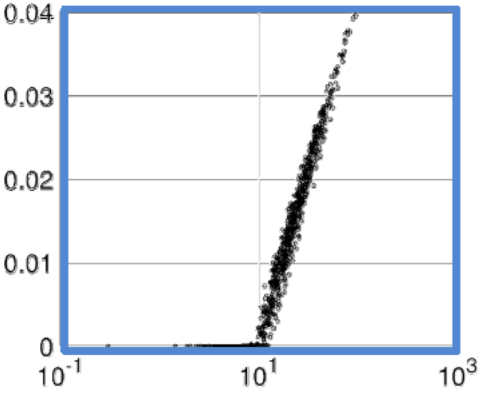
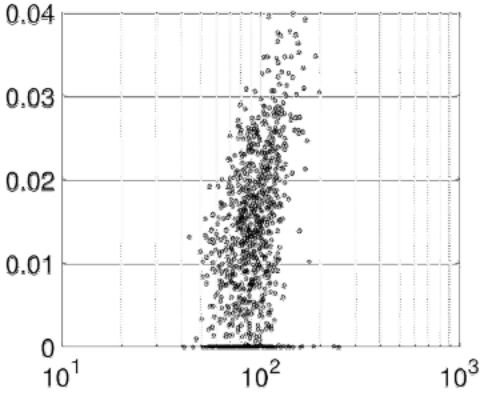
- Optimization problem:

$$\begin{aligned} &\text{minimize} && \textstyle\sum_{i,j} \text{cost}(\phi_{ij}) \\ &\text{subject to} && \lambda_{\max}\left(\begin{bmatrix} -D_1 & B_1 \\ \Psi_1 & B_2 - D_2 - \Phi - \Psi_2 \end{bmatrix}\right) < 0 \end{aligned}$$

Can be equivalently converted to a **geometric program**

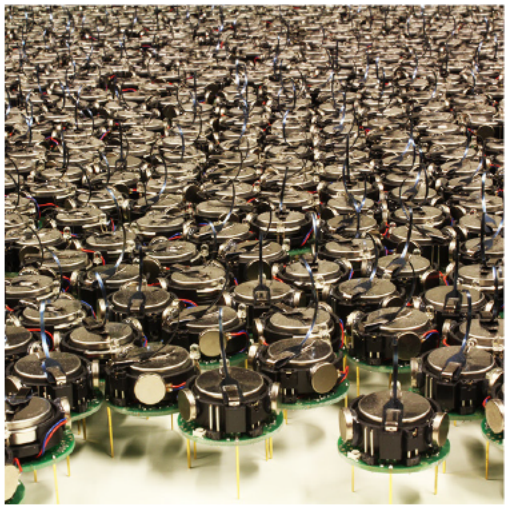
Optimal social-distancing rates ϕ_{ij}

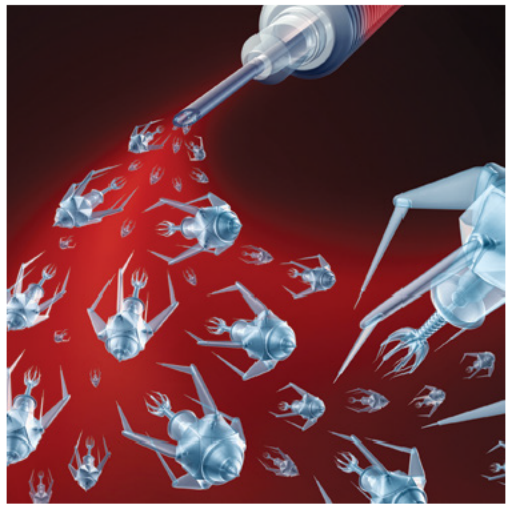
- Optimal investment and centralities

	Prod. of degrees of i and j	Prod. of eig. centralities of i and j	Edge-betweeness centrality of (i, j)
A Facebook network			
Erdös-Rényi random graph			

Swarms

Swarms

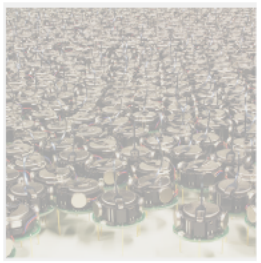
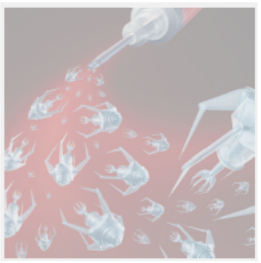


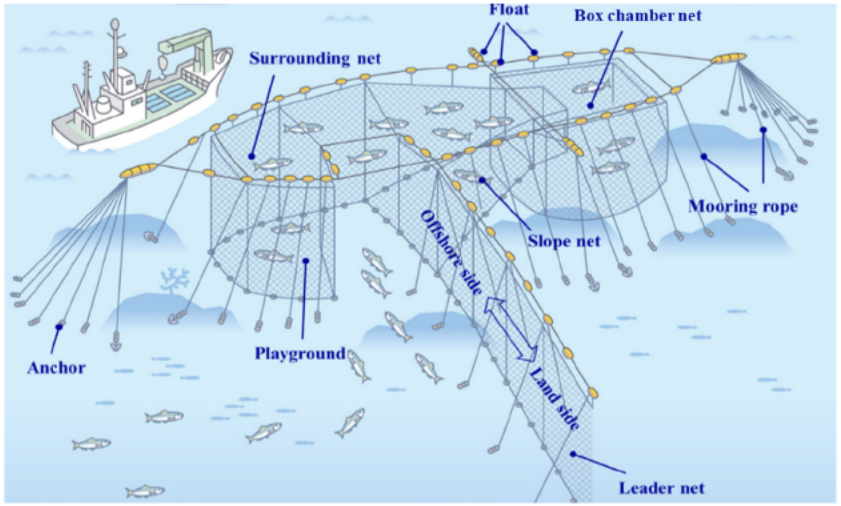


Swarm control







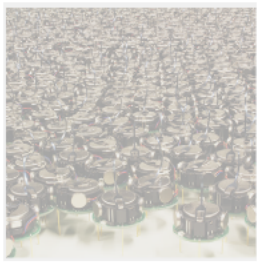
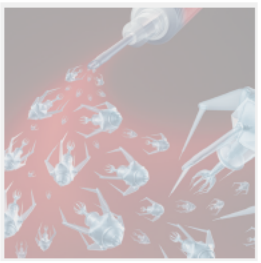
Set net fishing

- Current technology cannot control the type of fish entering a net
- Issue: Bycatch of unwanted fish species
- Control objective: **Selective capture** of target fish species while avoiding bycatch of unwanted species

Swarm control





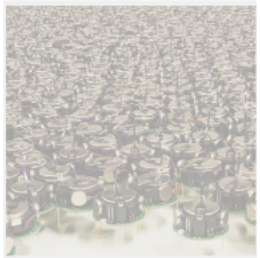
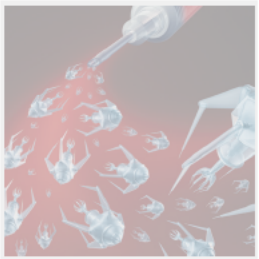
Locust management

- Desert locust outbreak affecting Africa every 10-20 years
- Issue: How to mitigate outbreaks effectively and efficiently?
- Control objective: Effective and efficient **outbreak prevention**

Swarm control





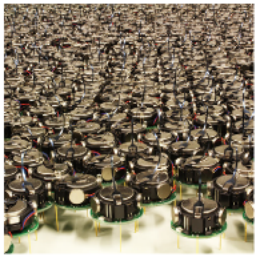
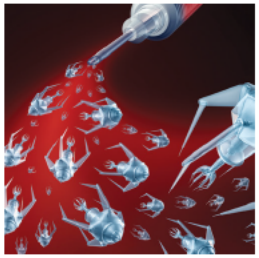
Crowd management

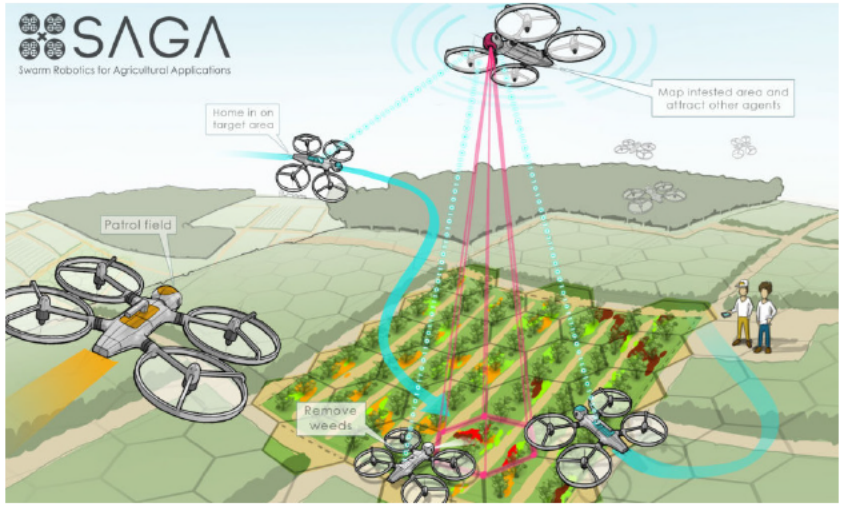
- Complex and dynamic behaviors influenced by individual actions and environmental factors
- Issue: Overcrowding cause safety hazards including stampedes and congestion
- Control objective: **Intervention** for safe and efficient movement

Swarm control





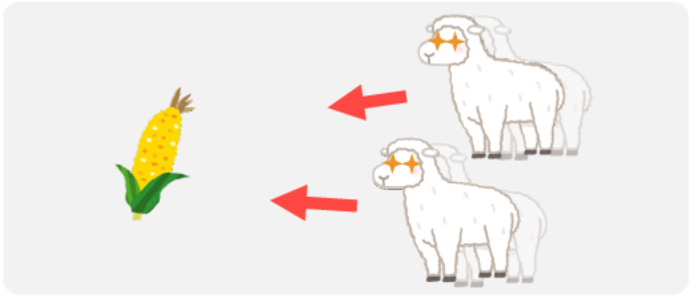


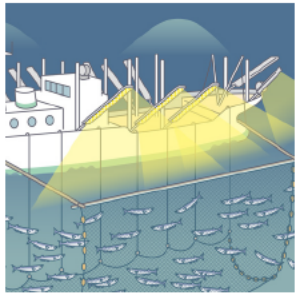
Swarm robot management

- Potential applications in rescue, environmental monitoring, agriculture, and space exploration
- Issue: Control with scalability and robustness overcoming hardware limitations and communication constraints

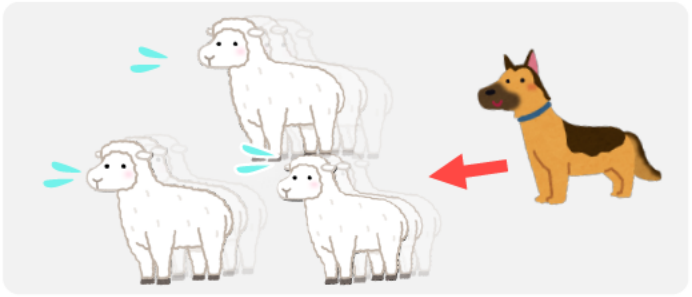
Control strategies: two critical choices

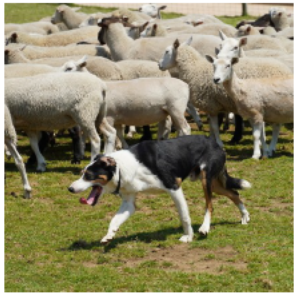
Attraction





Repulsion





Prominent example

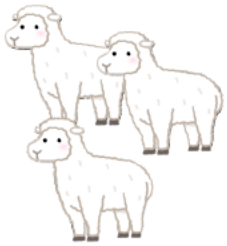
Sheepdog shepherding sheep

Shepherding problem

A simplified **model** problem for swarm control with repulsion

- Key elements

External agents exerting repulsion



Swarm agents to be guided

Goal area

- Problem statement: **Design a movement law** of an external mobile agent so that the swarm agents are guided into a prespecified goal area.
- Research objective: To extract a high-level knowledge useful for designing repulsion-based control strategies for swarm

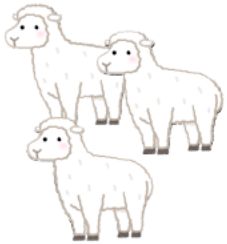
Long, Sammut, Sgarioto, Garratt, Abbass, "A comprehensive review of shepherding as a bio-Inspired swarm-robotics guidance approach," *IEEE Transactions on Emerging Topics in Computational Intelligence*, 2020.

Example

Assumptions

- Limited sensing ability
- Knows where the goal is

External agents



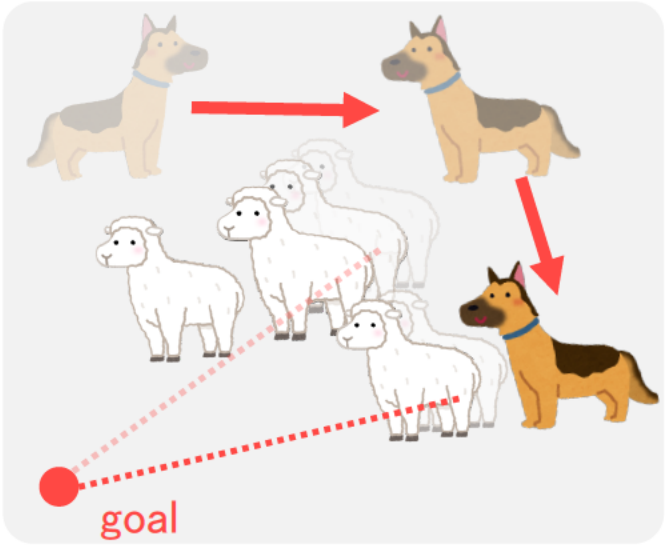
- Follows a Boid model
- Don't know where the goal is

Swarm agents

Goal area

Farthest Agent Targeting methodology

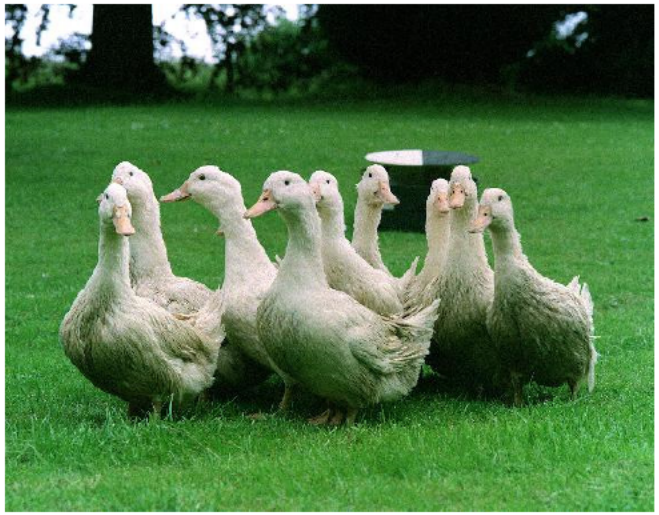
- "Chase the sheep furthest from the goal"
- Requires no knowledge on the other agents positions
- Simple but effective compared with conventional methodologies



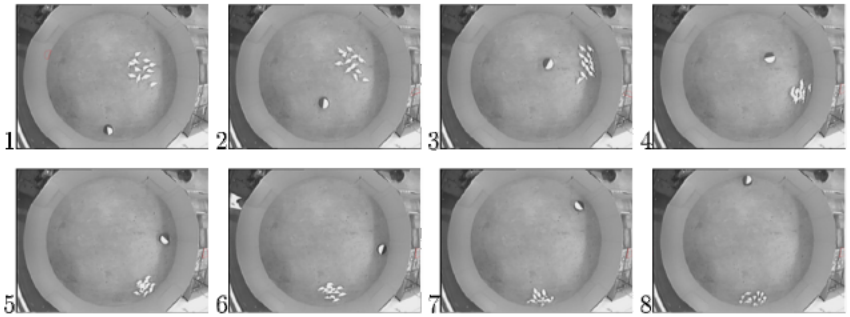
Tsunoda, Sueoka, Sato, Osuka, "Analysis of local-camera-based shepherding navigation," *Advanced Robotics*, 2018.

History

1990s: Foundation

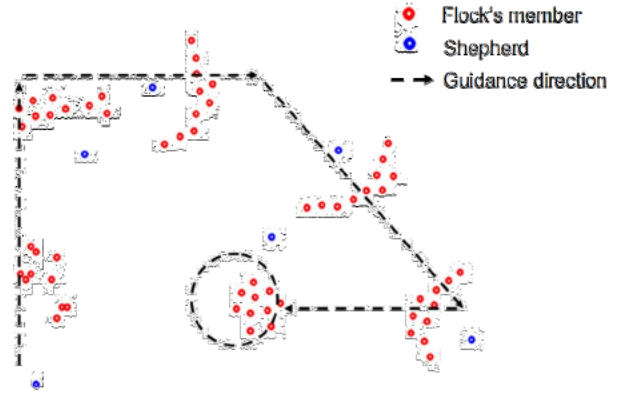


Robot Sheepdog Project (1996)

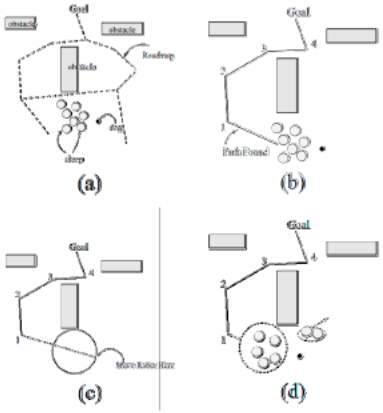


Rover herding the ducklets

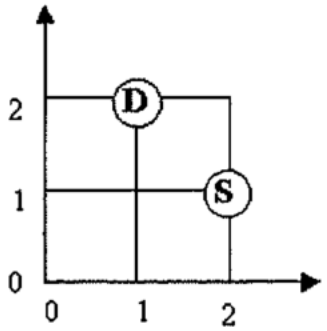
2000s: Simulation studies



Trajectory design [Miki, Nakamura, 2006]



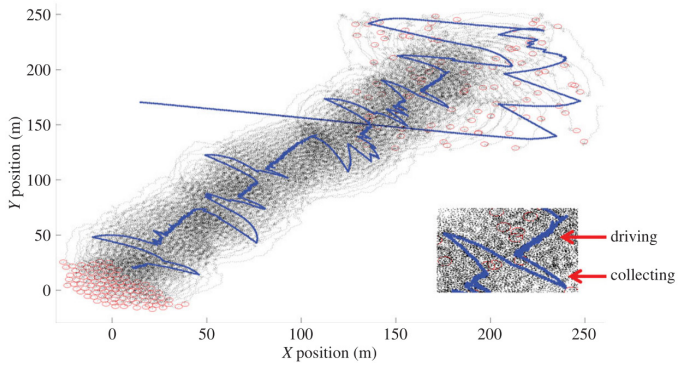
Trajectory design
[Bayazit et al., 2002]



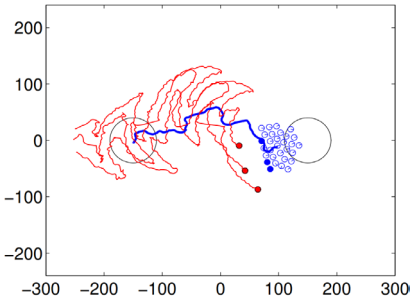
DP algorithm
[Kacharoo et al., 2001]

History

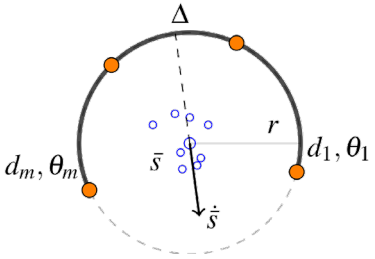
2010s: Advances



Drive & collect strategy [Strombom et al., 2014]

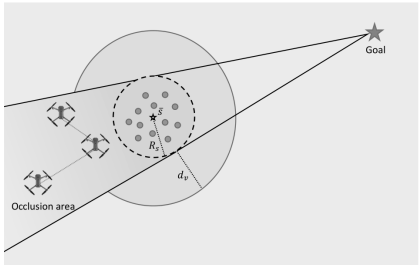


Multiple shepherds
[Lee, Kim, 2014]

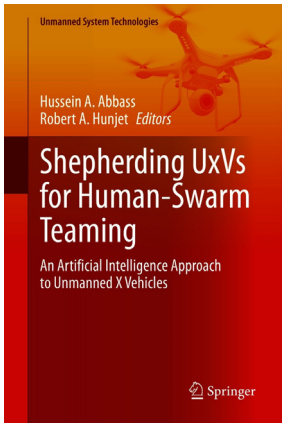


Control theory
[Pierson, Schwager, 2015]

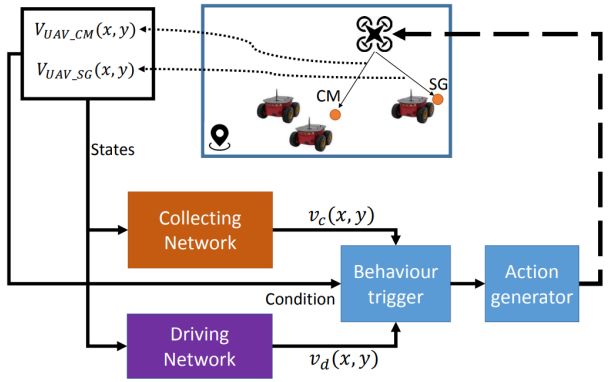
2020s: Modern developments



Occlusion-based approach
[Hu et al., 2020]



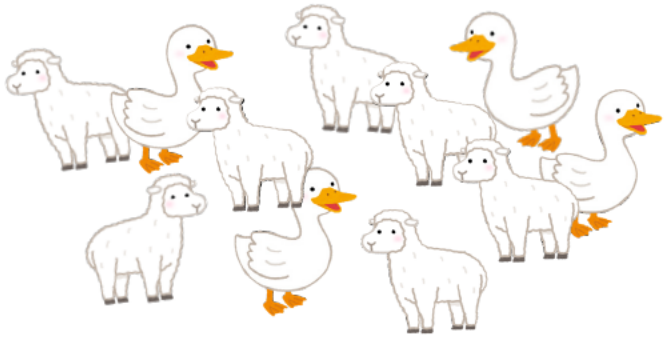
Book [Abbas, Hunjet, 2021]



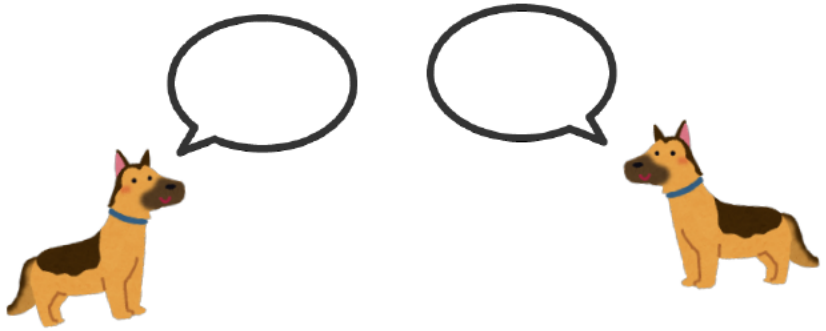
Reinforcement learning [Nguyen et al., 2022]

Open issues

Heterogeneity

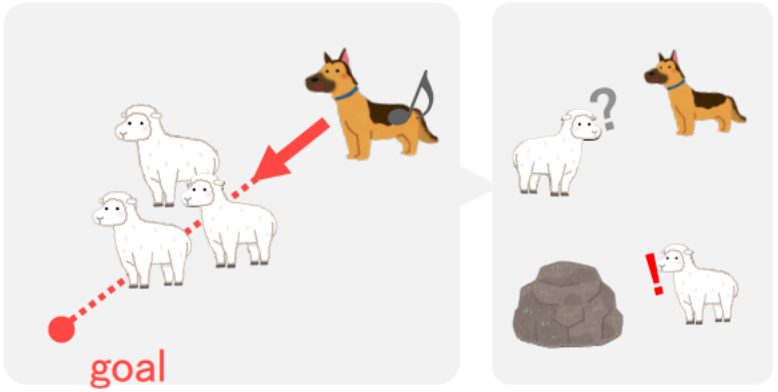


Communication



Sensing

Dynamic, complex environments



Heterogeneity (1/2)

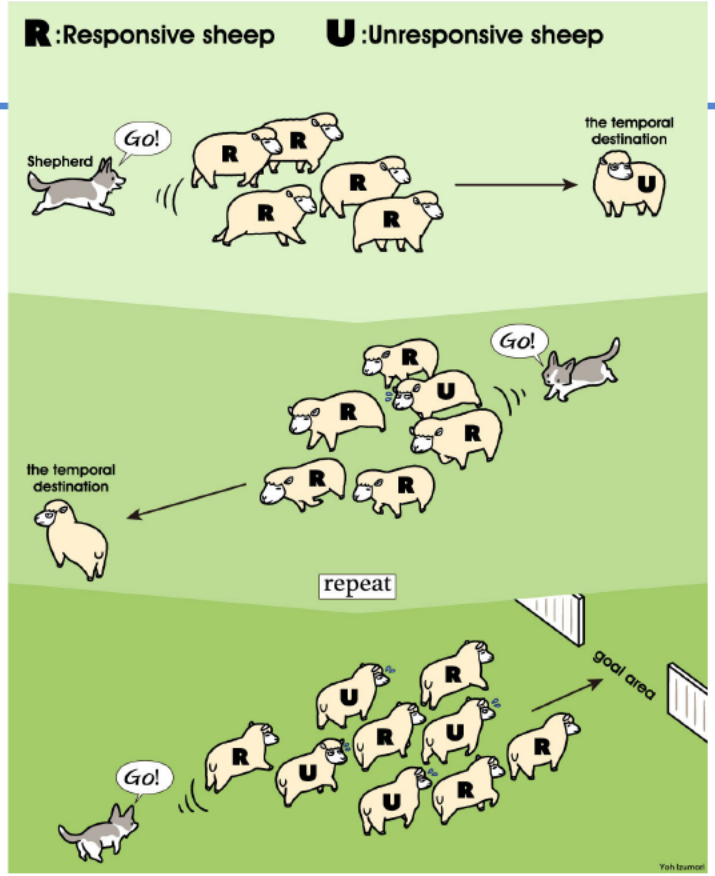
Conventional assumption

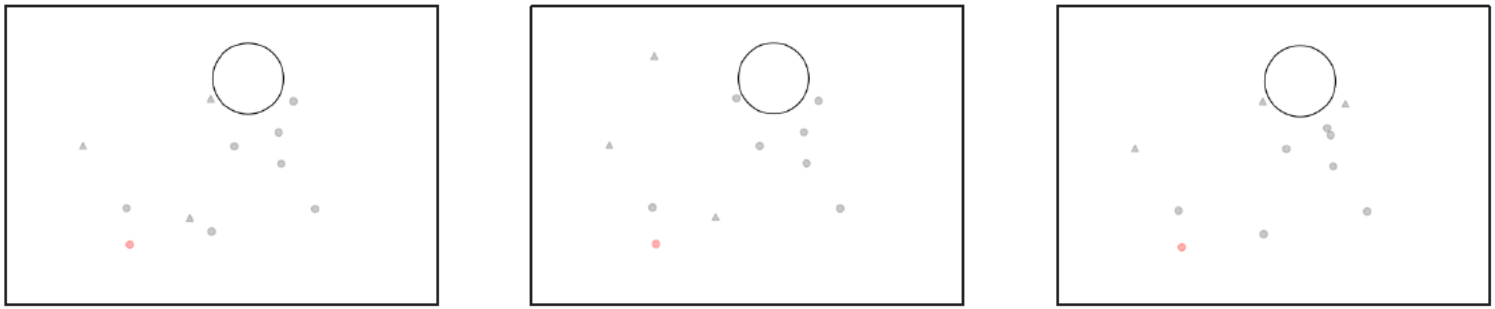
- No heterogeneity in sheep swarm

Reality

- Ineligible heterogeneity present
- Human crowd, sheep, fish, etc.

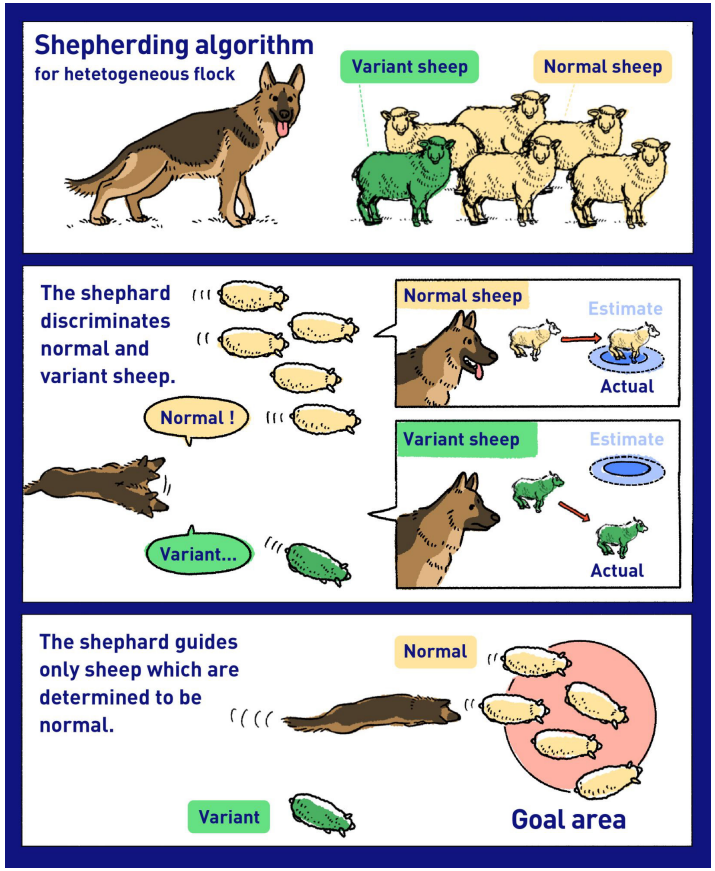
Designed movement law of shepherd to guide a whole heterogeneous swarm containing **unresponsive individuals** using cohesive forces present between sheep agents.

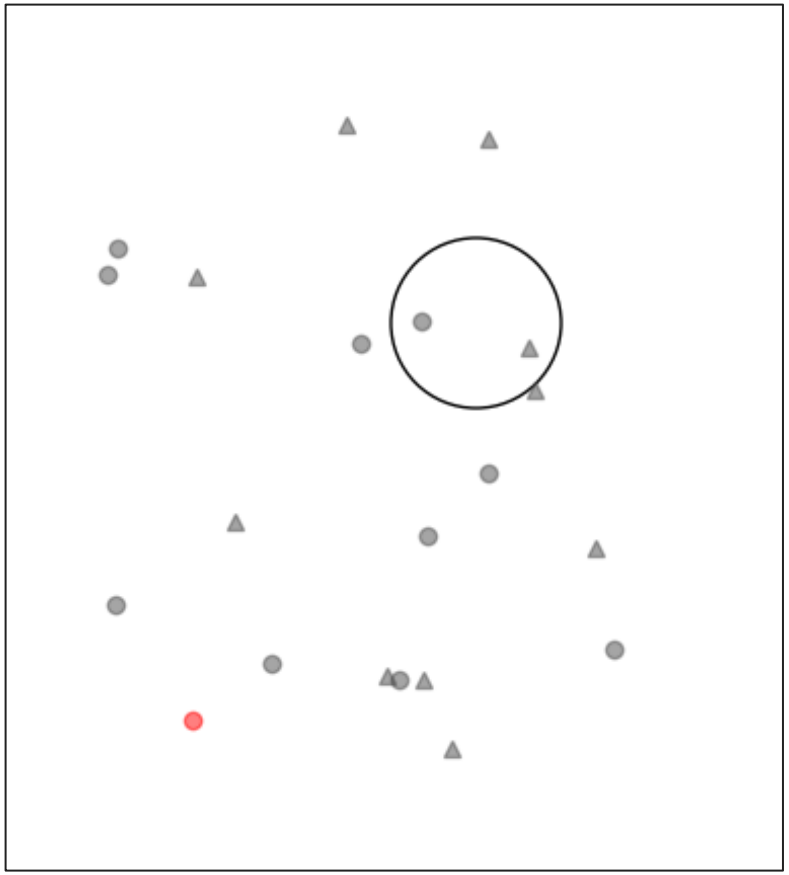




Himo, Ogura, Wakamiya, "Iterative algorithm for shepherding unresponsive sheep," *Mathematical Biosciences and Engineering*, 2022.

Heterogeneity (2/2)





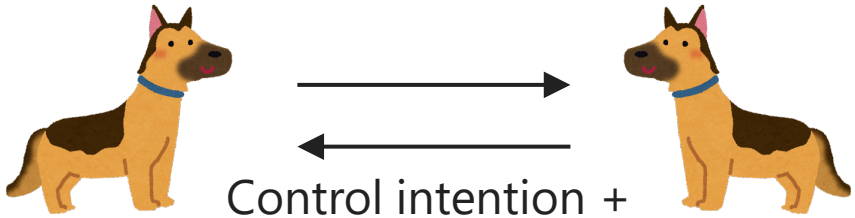
Designed movement law of shepherd to guide **only "guidable" individuals** within a heterogeneous swarm using model-based discrimination.

Fujioka, Ogura, Wakamiya, "Shepherding algorithm for heterogeneous flock with model-based discrimination," *Advanced Robotics*, 2023.

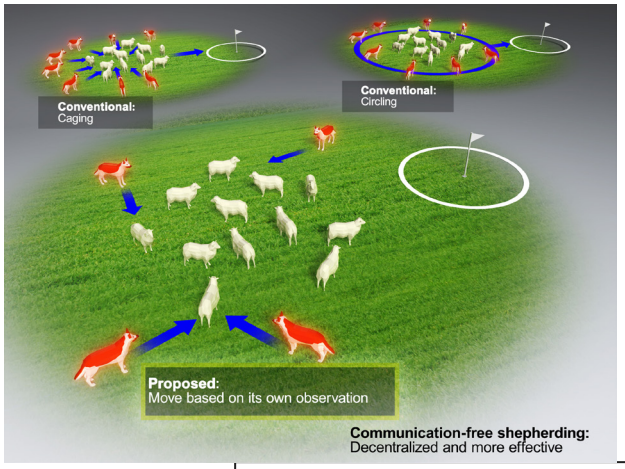
Communication

Conventional assumption

- Communication between shepherd agents [Lee, Kim, 2014]

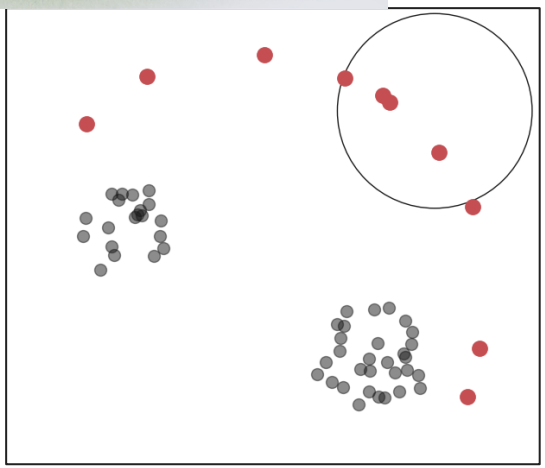


Control intention + information at hand.



Question

- Is communication indispensable element for multi-shepherd guidance?



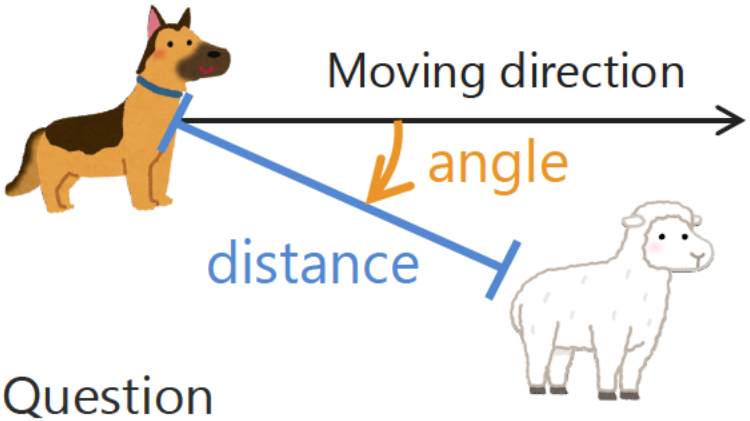
Designed movement law of **multiple** shepherds to guide a swarm under the constraints that **shepherds cannot communicate with each other**.

Li, Ogura, Wakamiya, "Communication-free shepherding navigation with multiple steering agents," *Frontiers in Control Engineering*, 2023.

Sensing

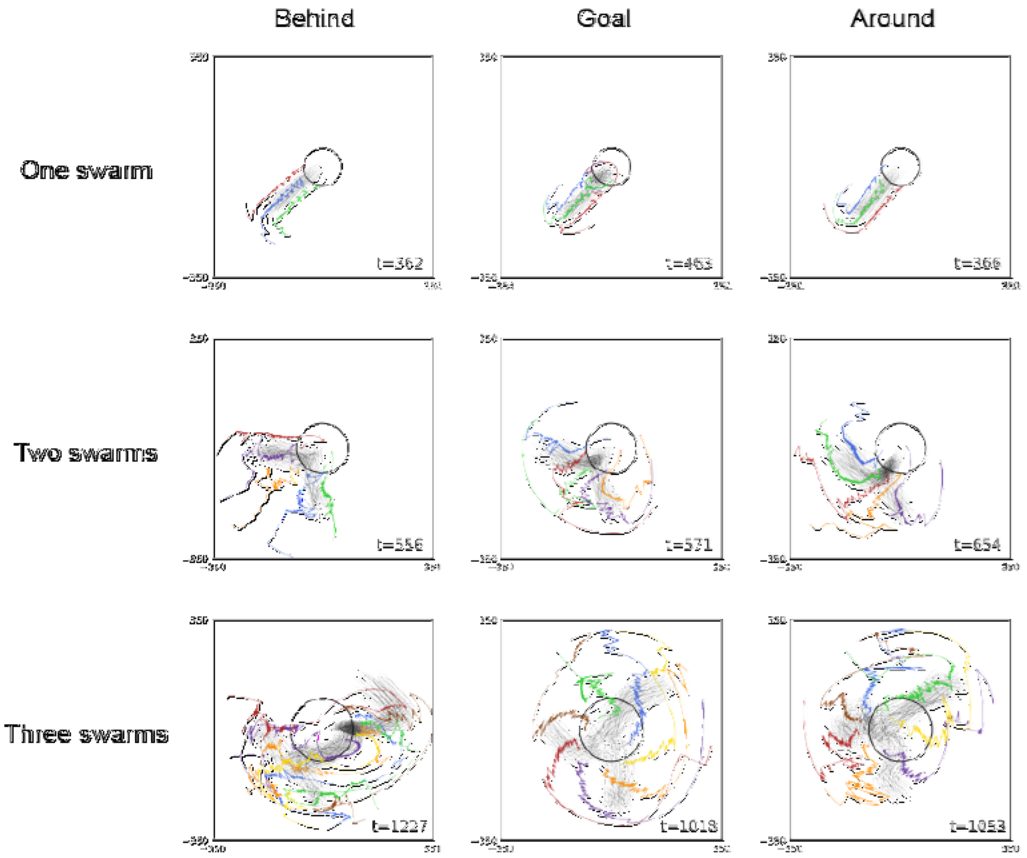
Conventional assumption

- Sheepdog can measure both distance and angle



Question

- Is distance measurement really necessary?



Designed movement law of shepherds to guide a swarm under the restriction that **only bearing-only measurements are available**.

Li, Ogura, Wakamiya, "Swarm shepherding using bearing-only measurements," *Philosophical Transactions of the Royal Society A*, 2024.

Yet another swarm: cyborg insects

Frame with reflective markers

Madagascan hissing cockroach

Battery and mounting plate

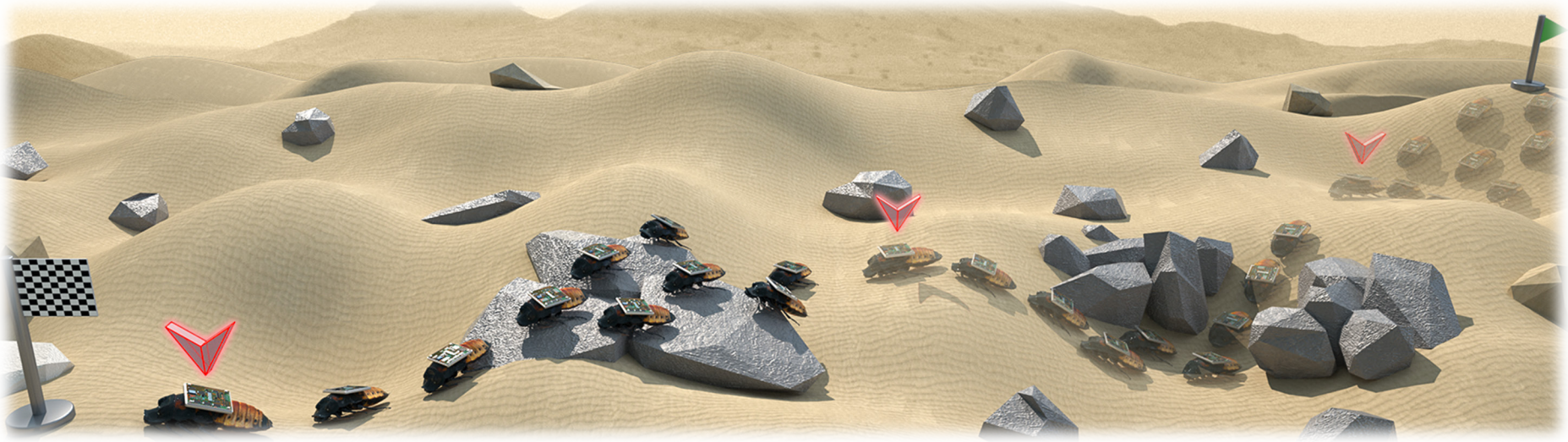
1 cm

Main controller

Bai, Ngoc, Nguyen, Le, Ha, Kai, To, Deng, Song, *Wakamiya, *Sato, and *Ogura, "Swarm navigation of cyborg-insects in unknown obstructed soft terrain," *Nature Communications*, 2025.

Problem setting

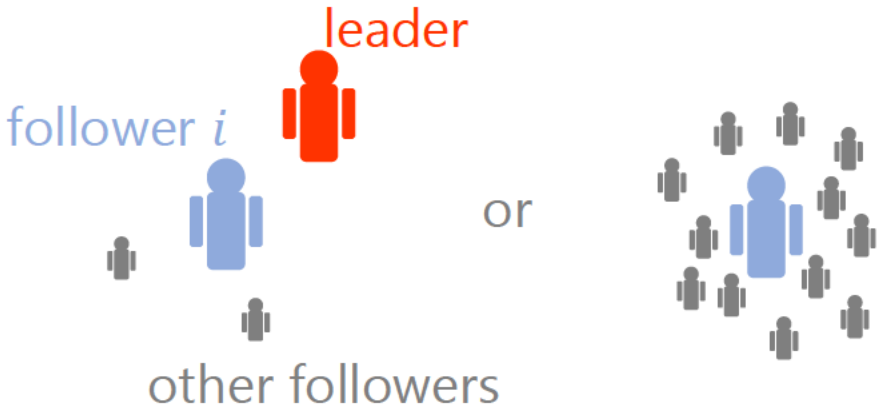
Drive a group of cyborgs (1 leader, N followers) to the goal in unknown environments



Control algorithm

Tour Group Inspired algorithm

- Inspired by how tourists (followers) follow a guide (leader) in a tour group
- How follower behaves
  - If leader is nearby or many neighbors around, take free motion



  - Else if leader is far but still visible (detectable), follow the leader
  - Else: leader is too far away (undetectable), move to the crowd

Proposal of an algorithm allowing free motion→ Enables the utilization of the natural behavior of Madagascar hissing cockroaches

Experiment

Weather

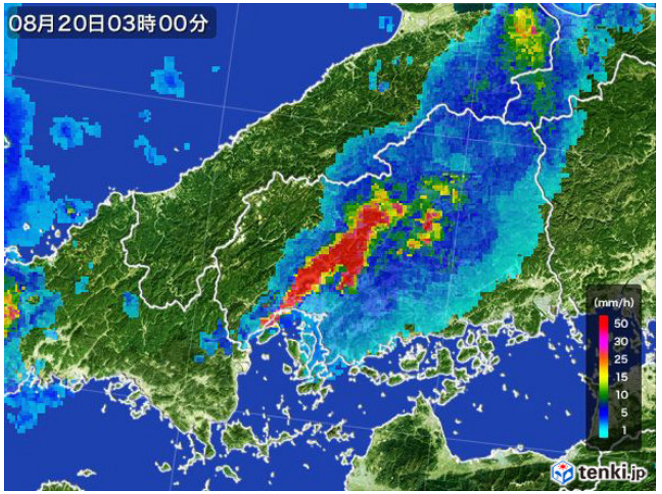
Disaster caused by climate change

Earth Will Continue to Warm and the Effects Will Be Profound

https://science.nasa.gov/climate-change/effects/

2014 Hiroshima landslides

- Heavy rain in Hiroshima caused catastrophic landslides
  - Significant loss of life and property
  - Over 200mm of rainfall in 3 hours
  - Triggered by stationary front and warm, moist air inflow.
- Localized rainfall overwhelmed early warning systems and disaster preparedness
- Highlights challenges in predicting and mitigating impacts of extreme weather events

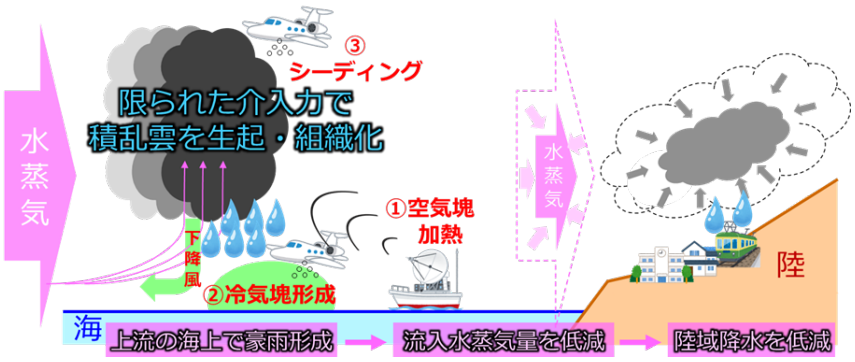


Raises questions about the potential role of weather control in disaster prevention and mitigation.

Two challenges toward weather control

Engineering

Weather control devices



- Weather intervention demands an enormous amount of energy.
- Current technology lacks devices capable of achieving this.
- What devices can be developed to enable weather control while ensuring affordability?

Optimization

Devices operation

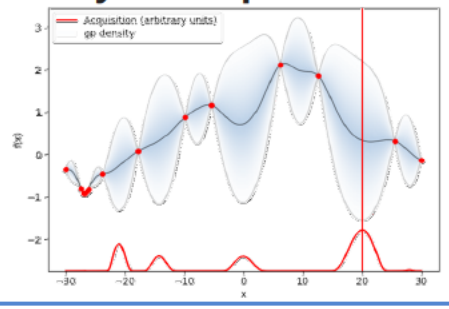
- Weather control needs a lot of energy, so wasting resources is not acceptable.
- Important to decide the best place, method, and timing for using these devices.
- A big optimization problem that needs careful planning.

Requires efficient methodology for optimizing intervention

Black-box optimization methodology

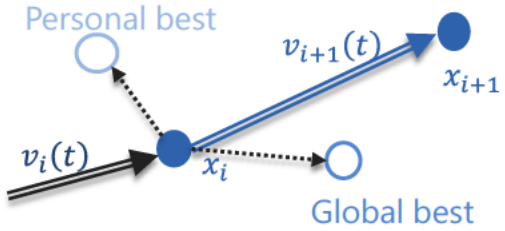
- Efficient approaches for exploration without requiring gradient information, suitable for weather intervention optimization.

Bayesian Optimization



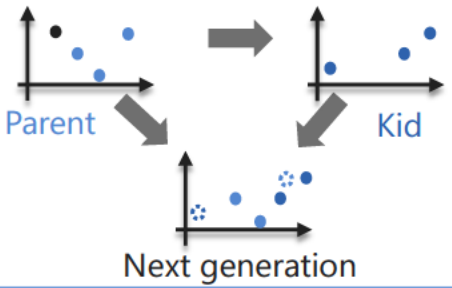
Balances exploration & exploitation using statistical models

Particle Swarm Optimization



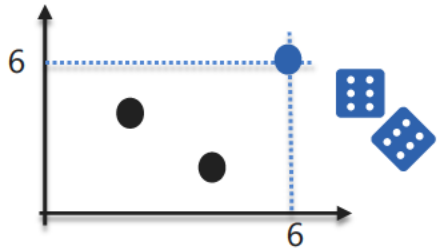
Mimics swarm behavior to balance global and local searches

Genetic Algorithm



Evolution-based method maintaining solution diversity

Random Search

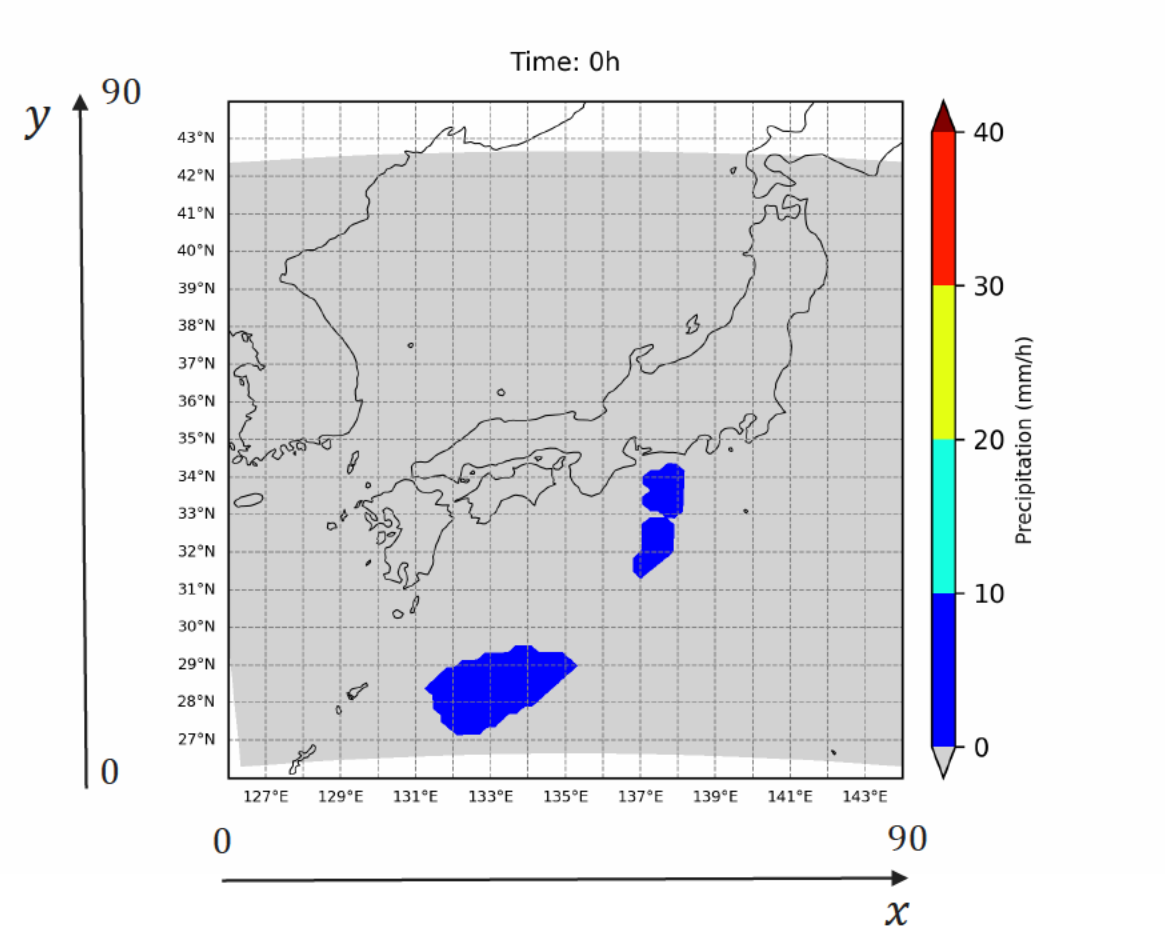


Covers the search space through random sampling

Control simulation

Scenario

- Typhoon Man-yi (2007)



Nagai, Higuchi, Okazaki, Ogura, and Wakamiya, presented in a domestic conference

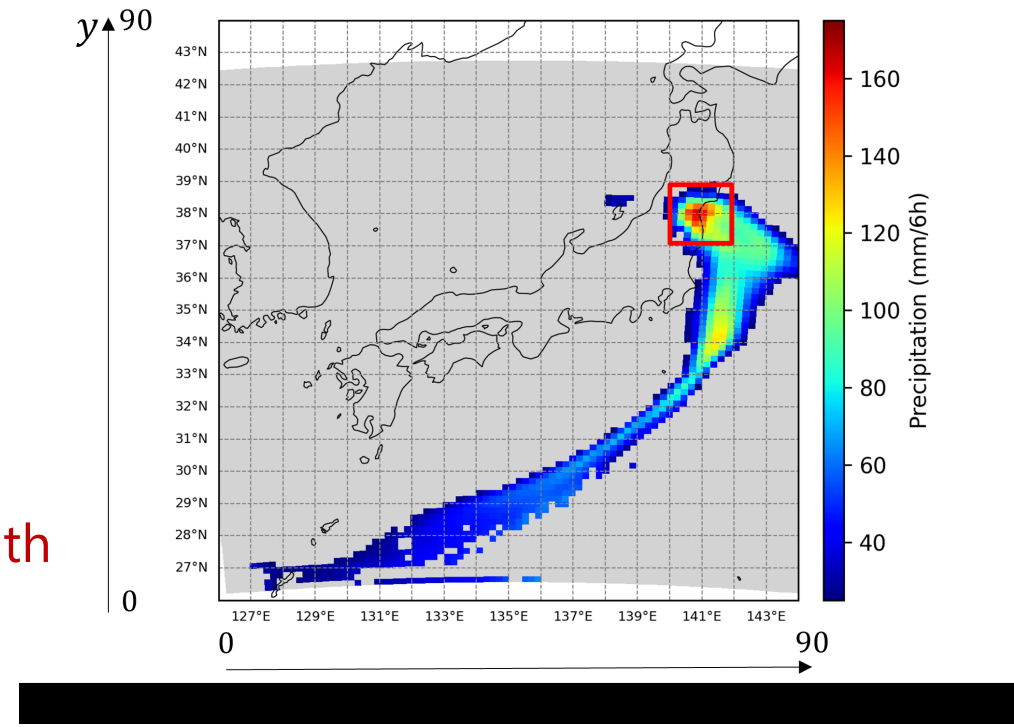
Control simulation

Control objective

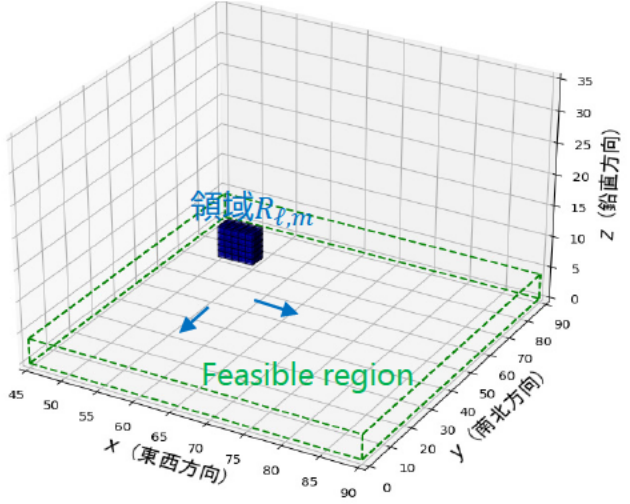
- Minimize the cumulative rainfall observed in the heavy rain regions of the Tohoku area.

Control input (control variables)

- MOMX: Atmospheric momentum in the x-direction $[\frac{kg}{m^2}/s]$ (≒ strength of wind in the east-west direction)
- MOMX: Atmospheric momentum in the y-direction $[\frac{kg}{m^2}/s]$ (≒ strength of wind in the north-south direction)



Control simulation



Intervention

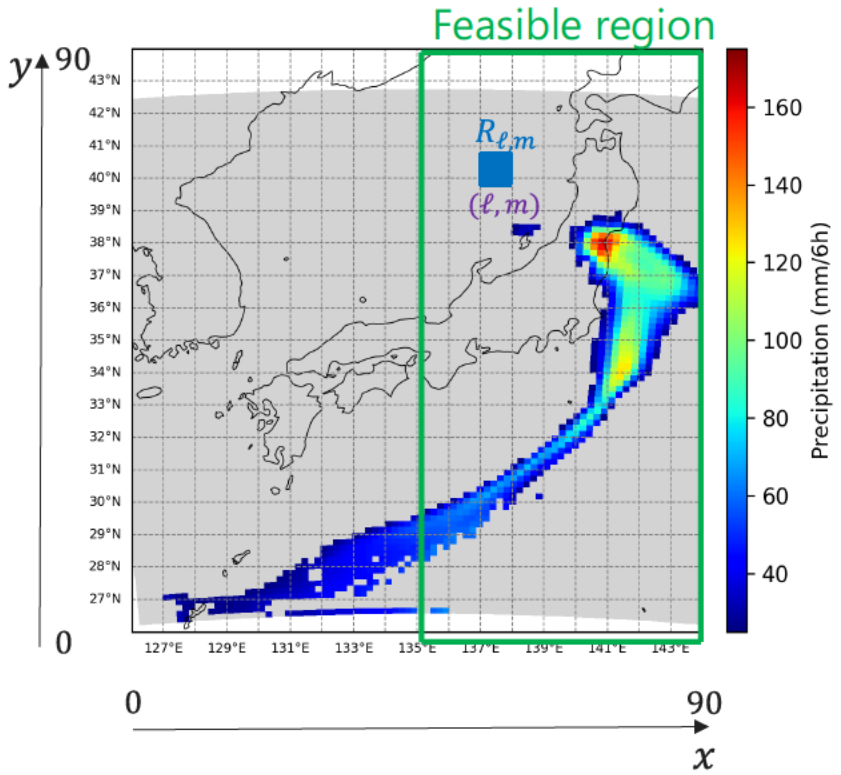
- Optimize area $R_{\ell,m}$ to be intervened.
- The area is chosen from

$$\{(x,y,z) \in \mathbb{Z}^3 | \ell \leq x \leq \ell + 4, m \leq y \leq m + 4, 0 \leq z \leq 4\}$$

and is updated every hour.

Control input $u = (d_x, d_y, \ell, m)$

- MOMX $-20 \leq d_x \leq 20$
- MOMY $-20 \leq d_y \leq 20$
- x-coordinate $45 \leq \ell \leq 85$
- y-coordinate $0 \leq m \leq 85$

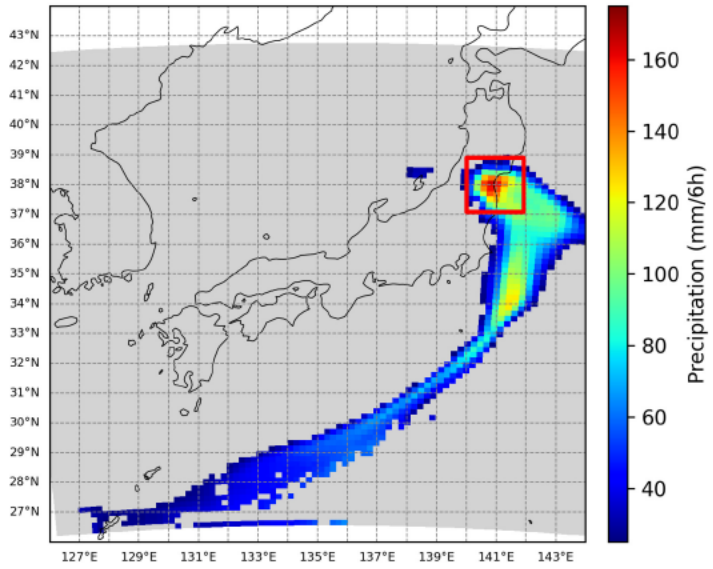


Result

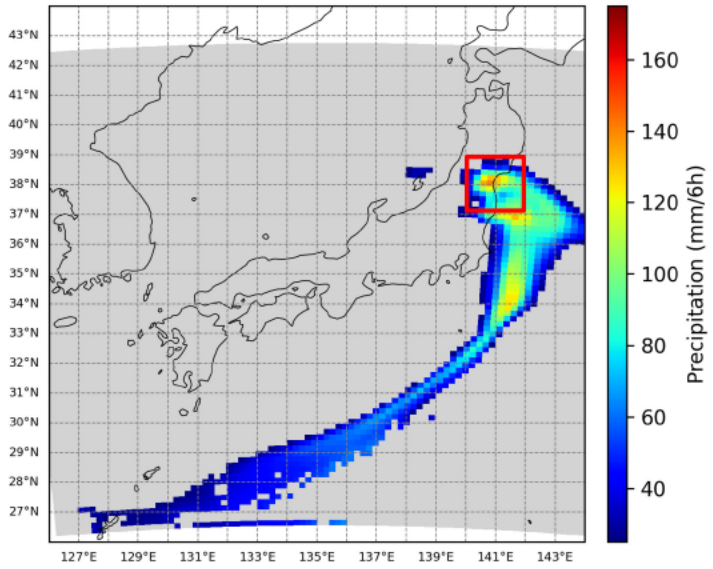
6-hour cumulative, post-control rainfall

- Simulations were conducted 10 times for each method.
- Using Bayesian optimization, a maximum reduction of 15.59% in cumulative rainfall was observed.

Before control

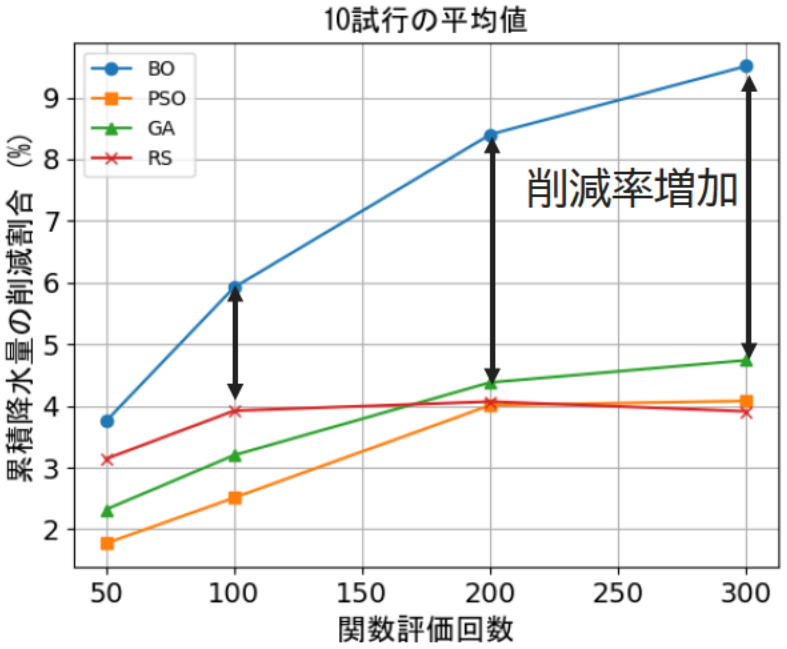


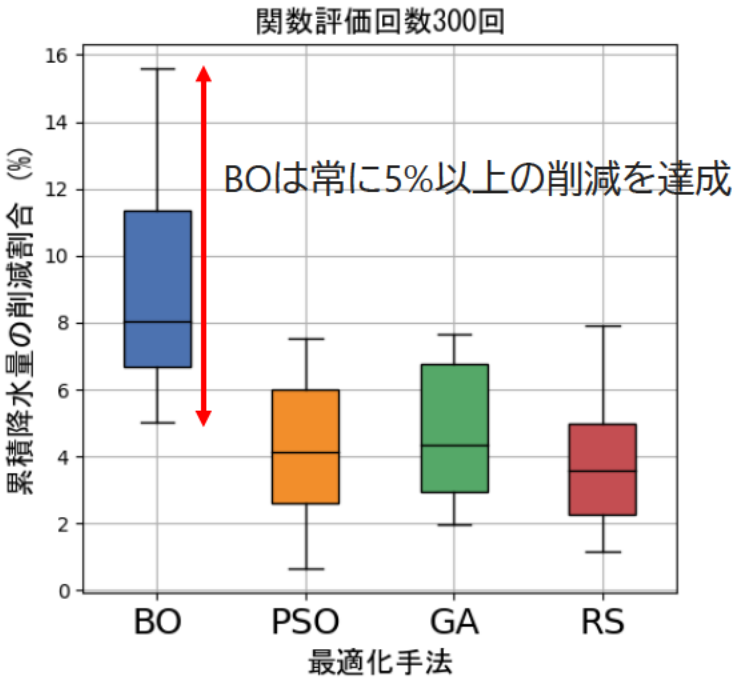
After control



Simulation

Comparison of Reduction Rates

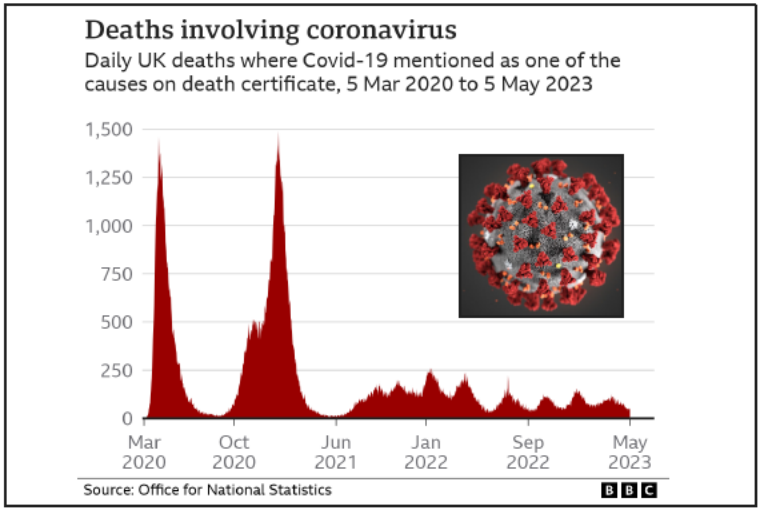




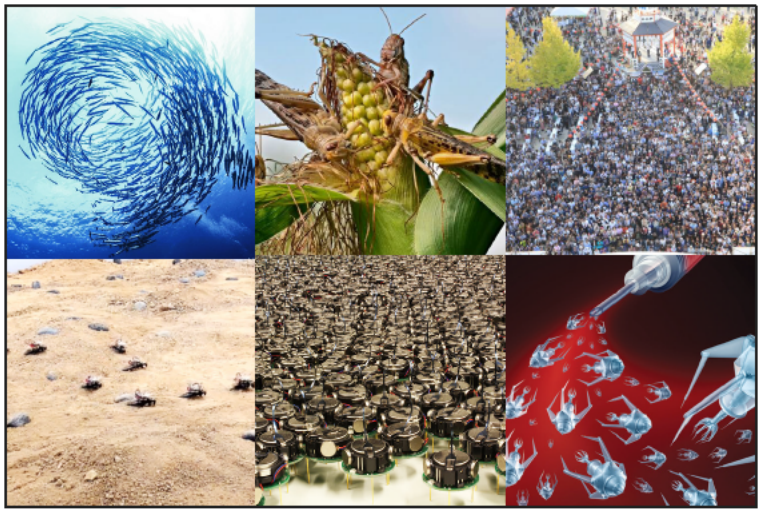
Suggests potential effectiveness of Bayesan Optimization in the context of weather-intervention design.

Conclusion

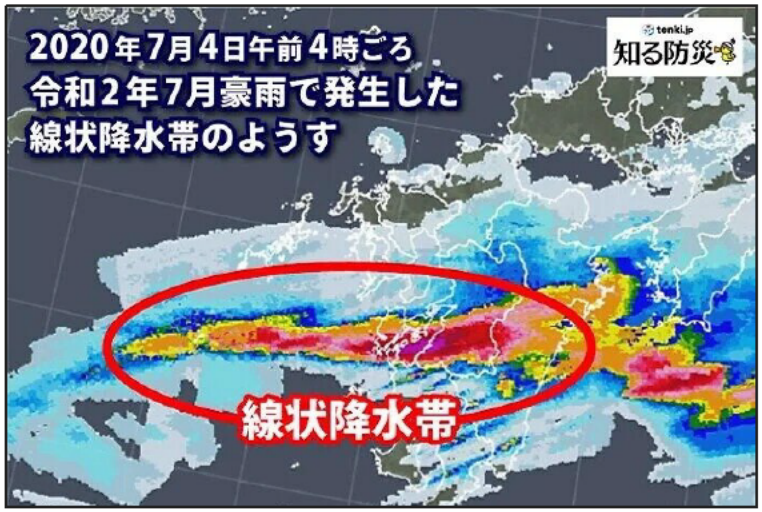
Conclusion



Epidemics



Swarms



Weather