

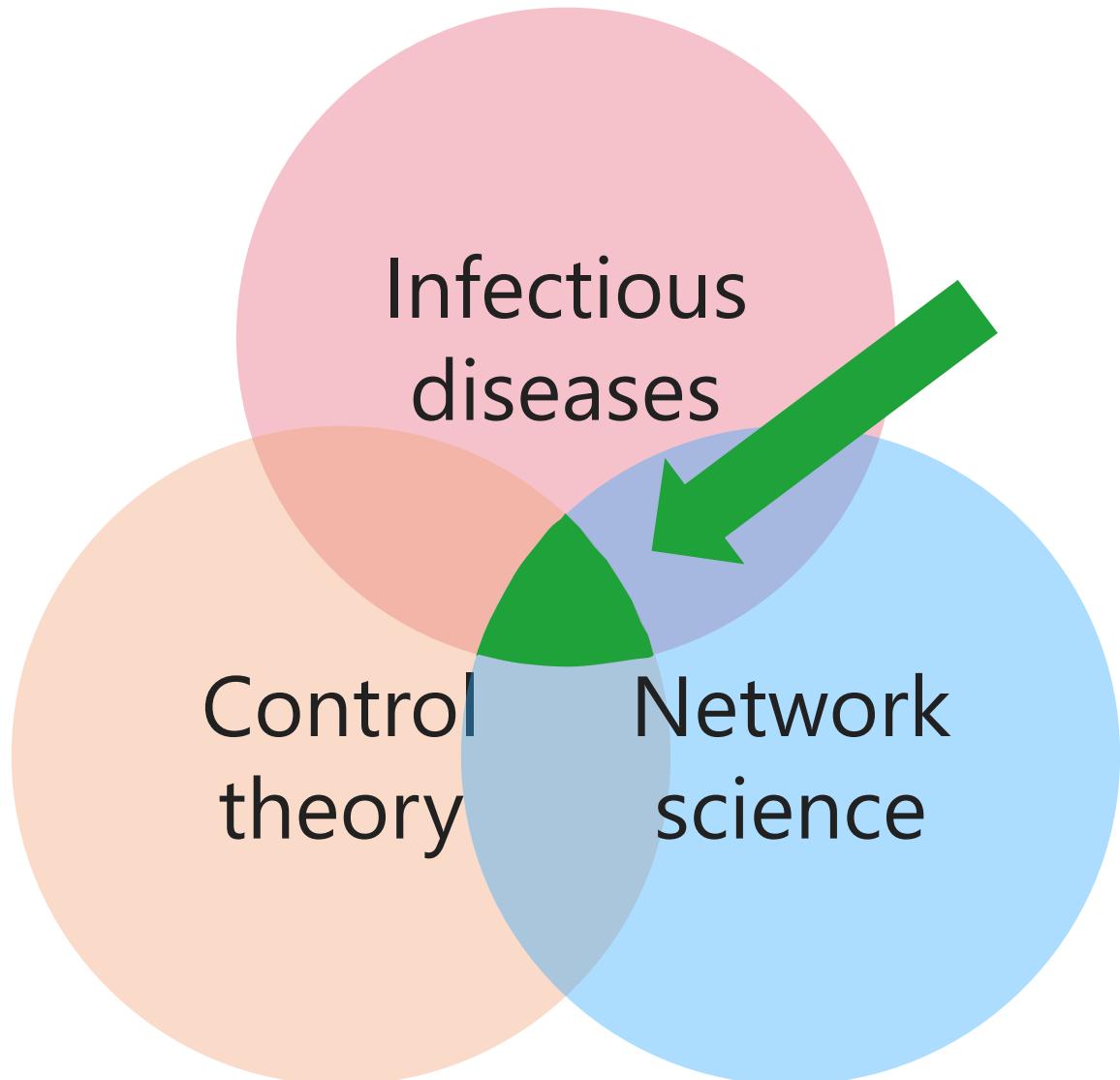
Modelling, analysis, and control of networked epidemic processes

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In today's seminar...

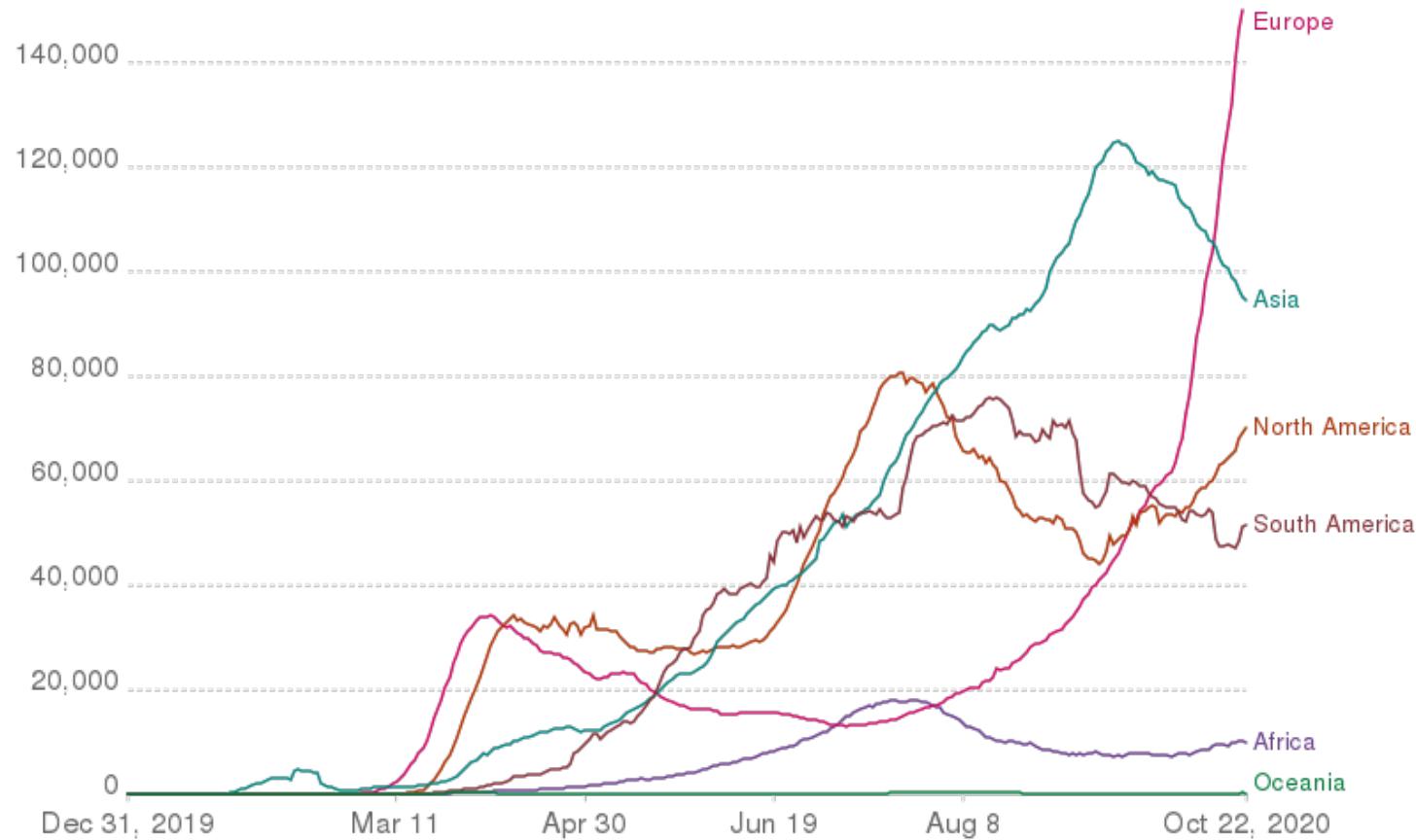
2



Infectious Diseases

Daily new confirmed COVID-19 cases

Shown is the rolling 7-day average. The number of confirmed cases is lower than the number of actual cases; the main reason for that is limited testing.



Source: European CDC – Situation Update Worldwide – Last updated 22 October, 10:34 (London time)

Epidemic curve showing the 7 day rolling average of daily new cases of COVID-19 by continent [Our World in Data]

We want vaccine

5

天然痘

1958年～世界天然痘根絶計画を実施。

世界を挙げて徹底的なワクチン接種を実施。

400万人
1958年 推定死者数(世界)



根絶
1980年5月 根絶



[参考] 国立感染症研究所HP

ポリオ

1988年～世界ポリオ根絶計画を実施。

世界を挙げて予防接種を実施する取り組みを続け、症例数は28年間で99%減少。世界からポリオを根絶するまであと一歩。

35万件
1988年 症例数(世界)

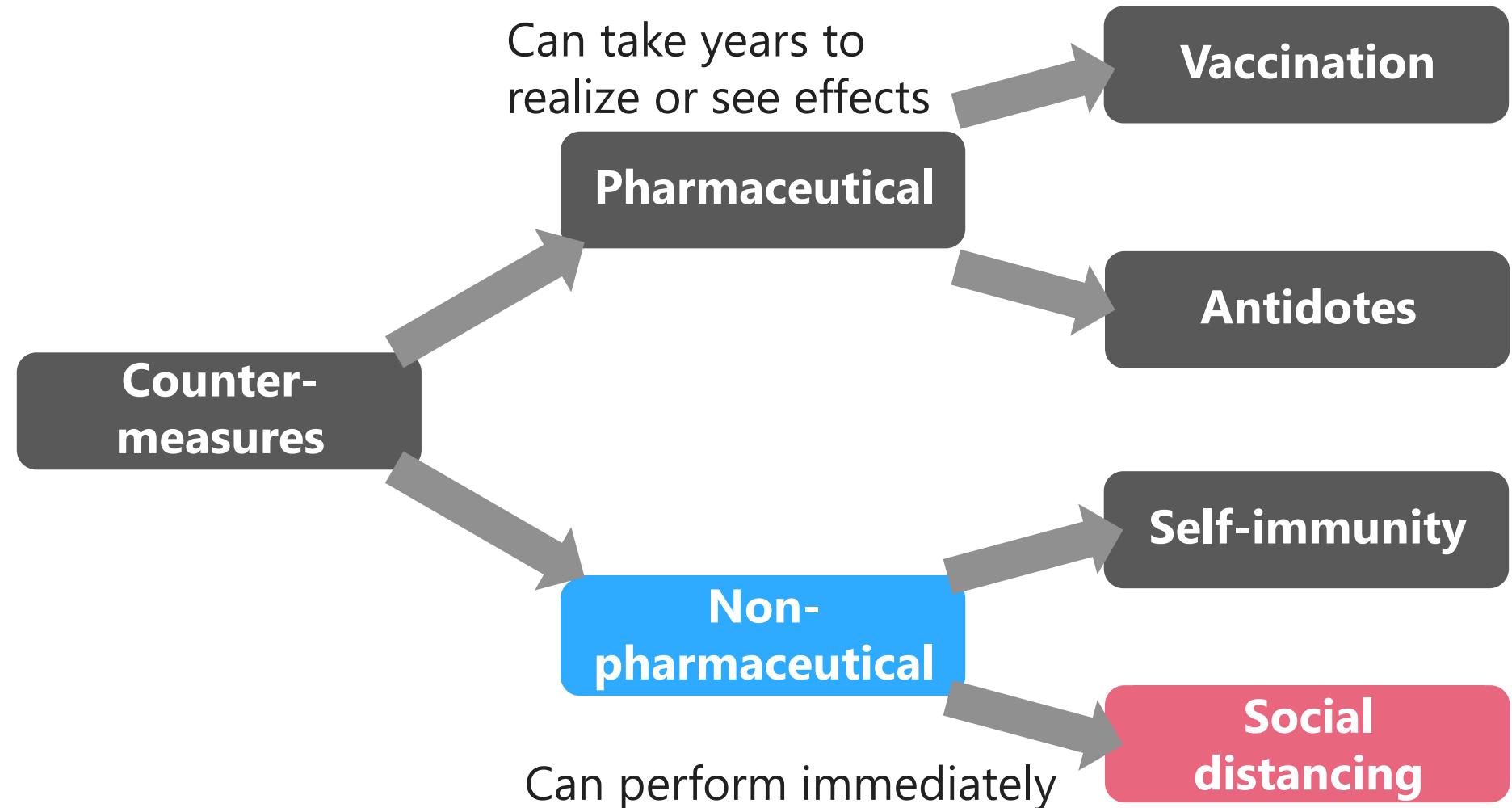
→ 27件
2016年 症例数(世界)

[参考] 日本ユニセフ協会HP

https://www.biken.or.jp/about_vaccine/support-society

How to contain infectious diseases

6



Social distancing

Keep a safe distance between you and others



Wearing masks

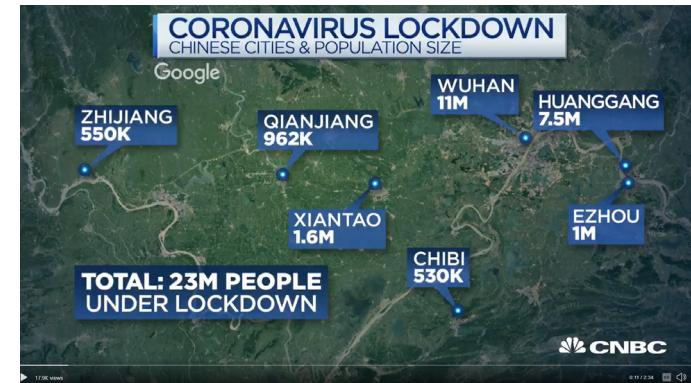
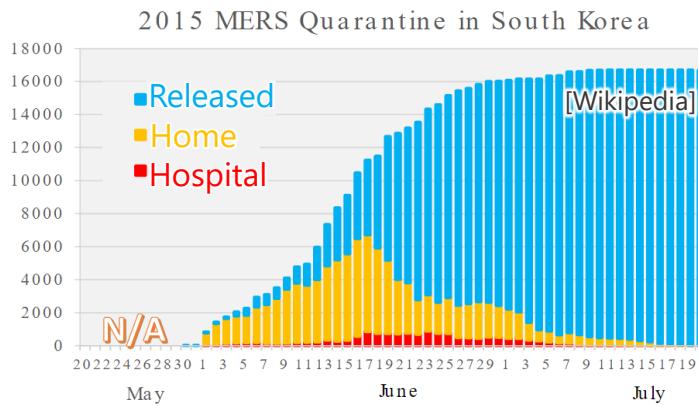


School closures



Quarantine

■ MERS outbreak, South Korea ■ COVID-19



Social distancing

- Saying is one thing and doing another

Who?

How strict?

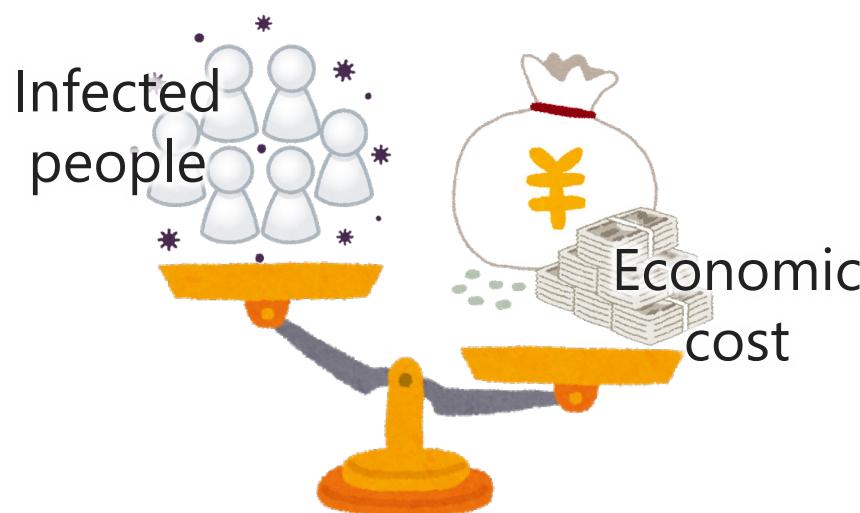
How long?

**Changing
situation**

**Information
uncertainty**

Big data

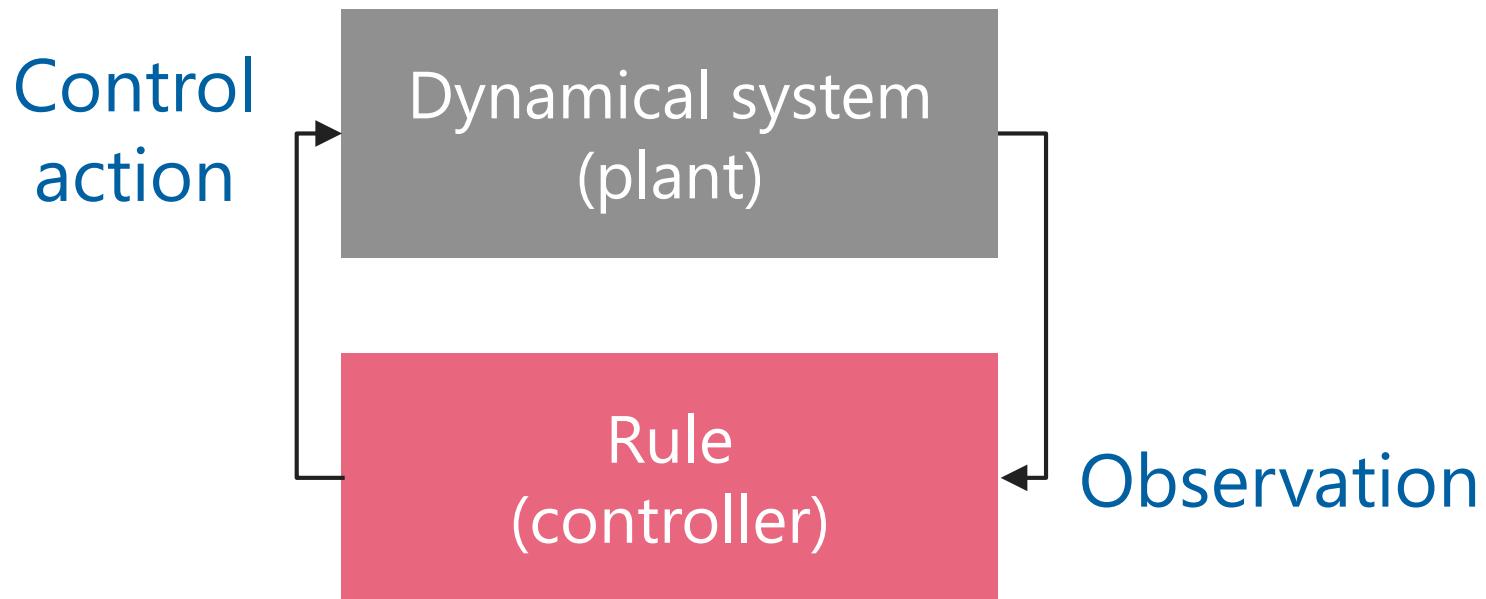
- Trade off: cost and benefit



Control theory

Control theory

- Deals with dynamical systems
 - Differential or difference equations
- Control rules to be designed (controller)
 - Make the plant behave in a desired manner
 - Costs and constraints
- Feedback control



Some applications

11

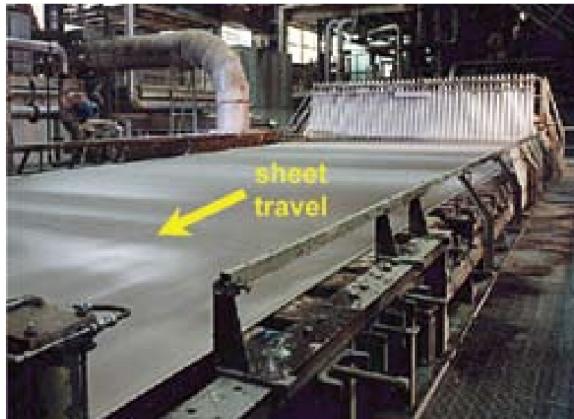
Auto-tuning controller



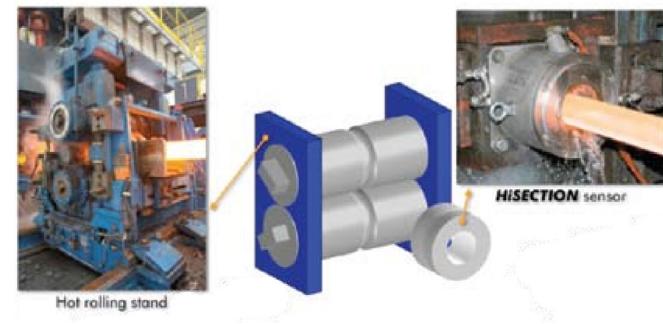
Relay Auto-tuning

Figure 2: PID auto-tuners

Paper machines



Steel rolling mills



Satellites

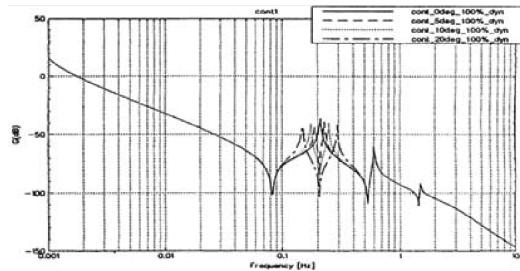


Figure 1: Structural flexible modes (above) of Astrium communication satellite platform Eurostar 2000+ (left). The shifting of frequency modes corresponds to different angular positions of the solar arrays. Source: EADS

F-35



F-35

Joint direct attack munition

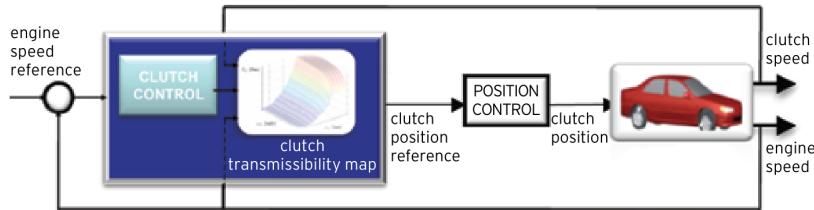


Laser guided MK - 82 scores direct hit against a moving target during tests at Eglin AFB

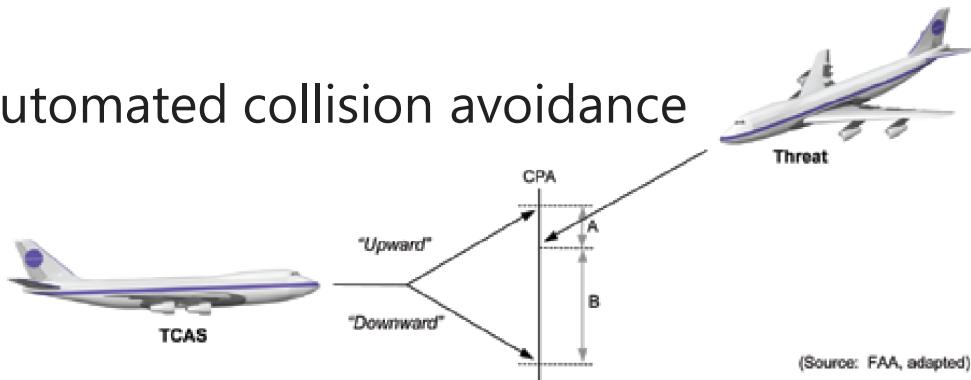
Affordable hit-to-kill accuracy minimizes collateral damage

Some applications

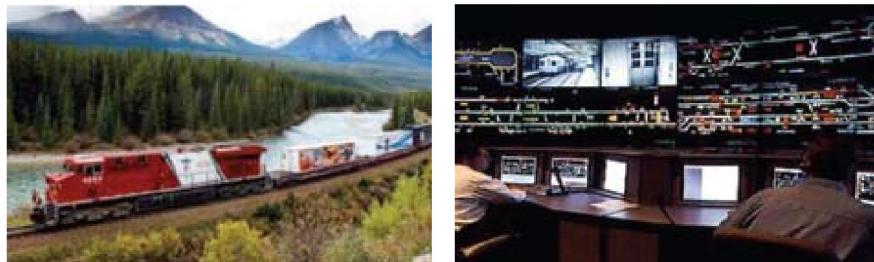
Automated manual transmissions



Automated collision avoidance



Trip optimizer for railroads



F1



Digital signal processing

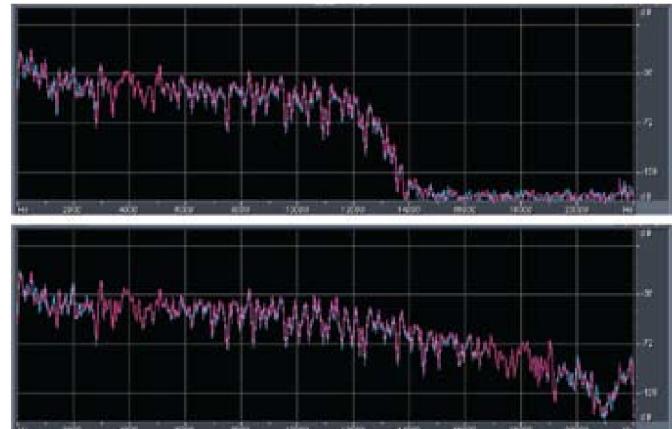
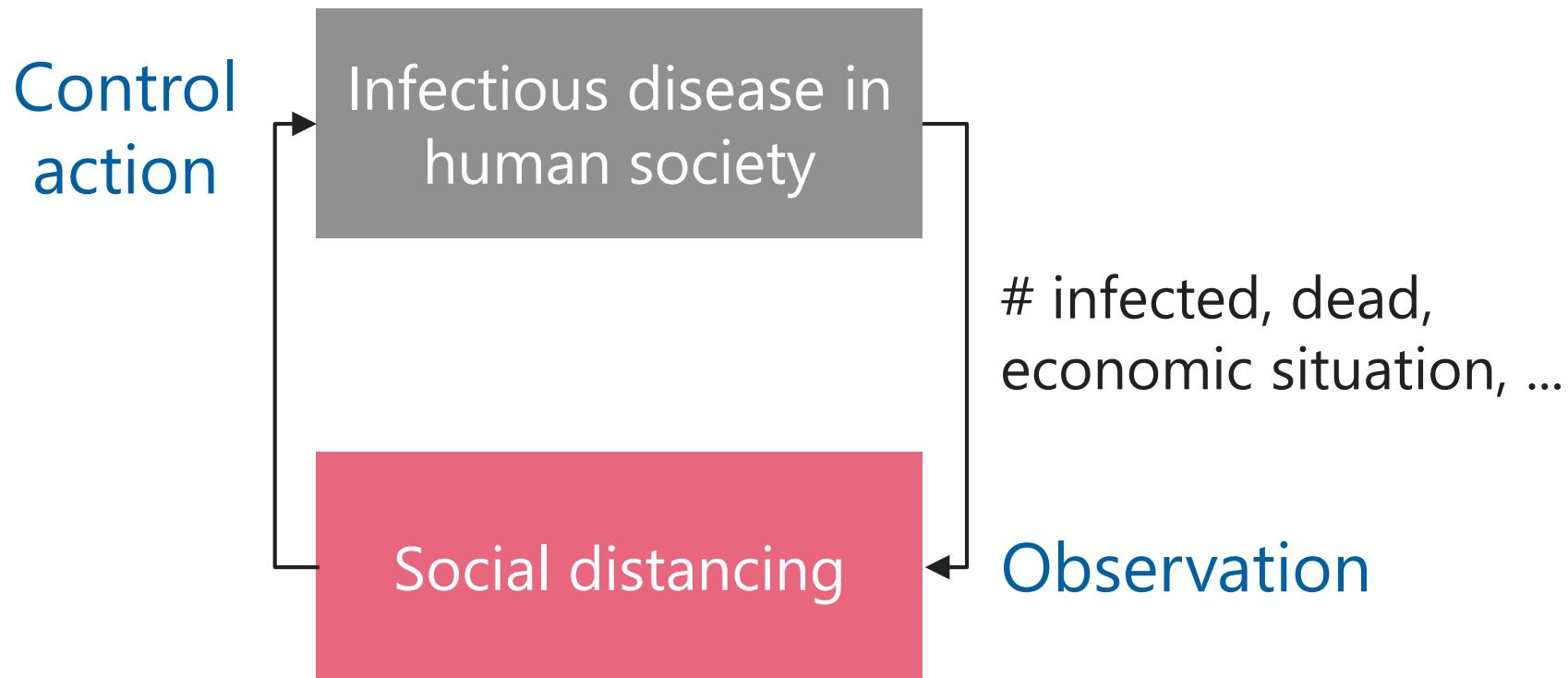


Figure courtesy of Sanyo Corporation.

Social distancing as a controller?

13



Mathematical model

Human society as a complex network

15

SOCIETY

Factoid:



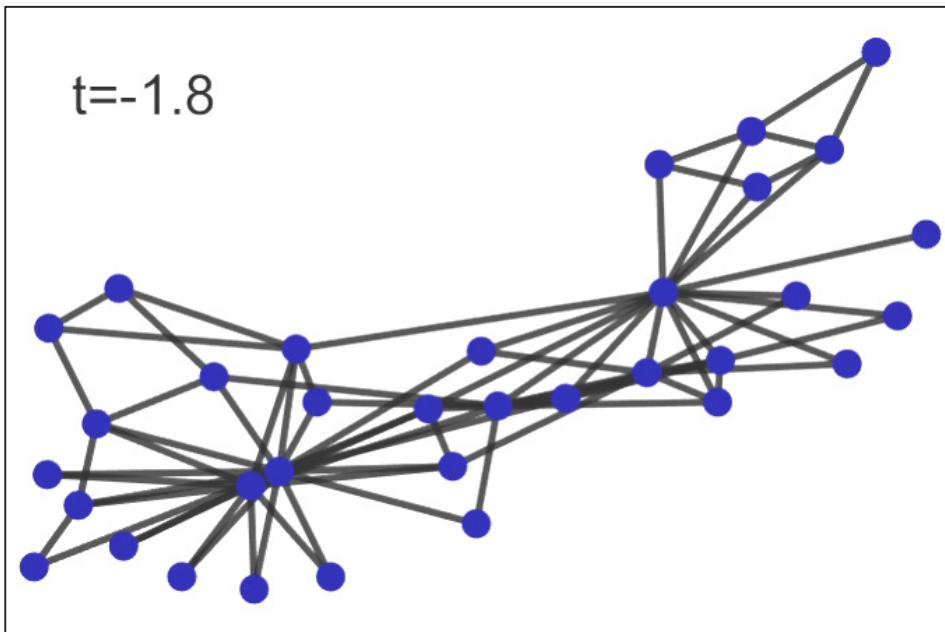
The “Social Graph” behind Facebook

Keith Shepherd's "Sunday Best". <http://baseballart.com/2010/07/shades-of-greatness-a-story-that-needed-to-be-told/>

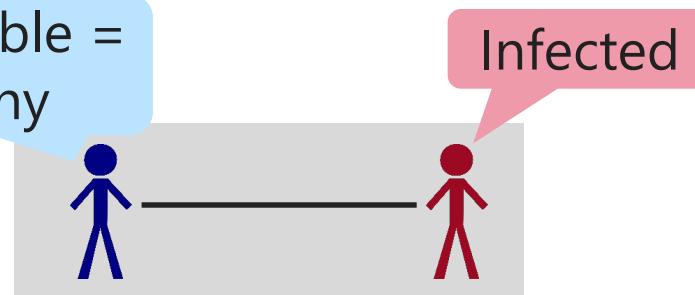
Network Science: Introduction

Graph + node dynamics

- A standard model
 - Nodes = individuals
 - Edges = relationships



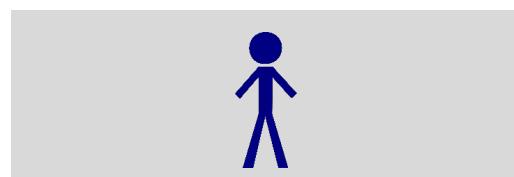
Susceptible =
healthy



Infection rate β

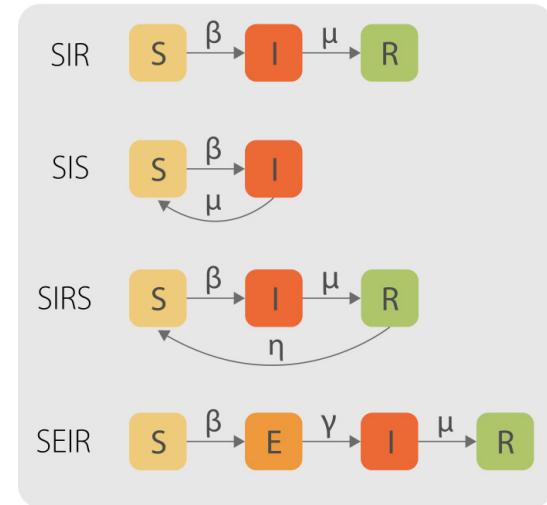


Recovery rate δ

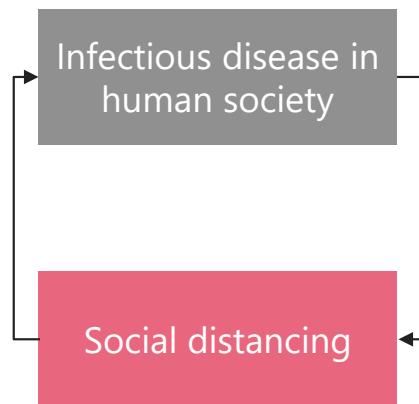


Why SIS model?

- Analytically tractable
 - Only two states: susceptible and infected
- Often used in Systems and Control Theory
 - Not realistic but would capture something
 - SIR also used in Network Science
- No social distancing dynamics
 - Let us “attach” a controller on top of SIS model



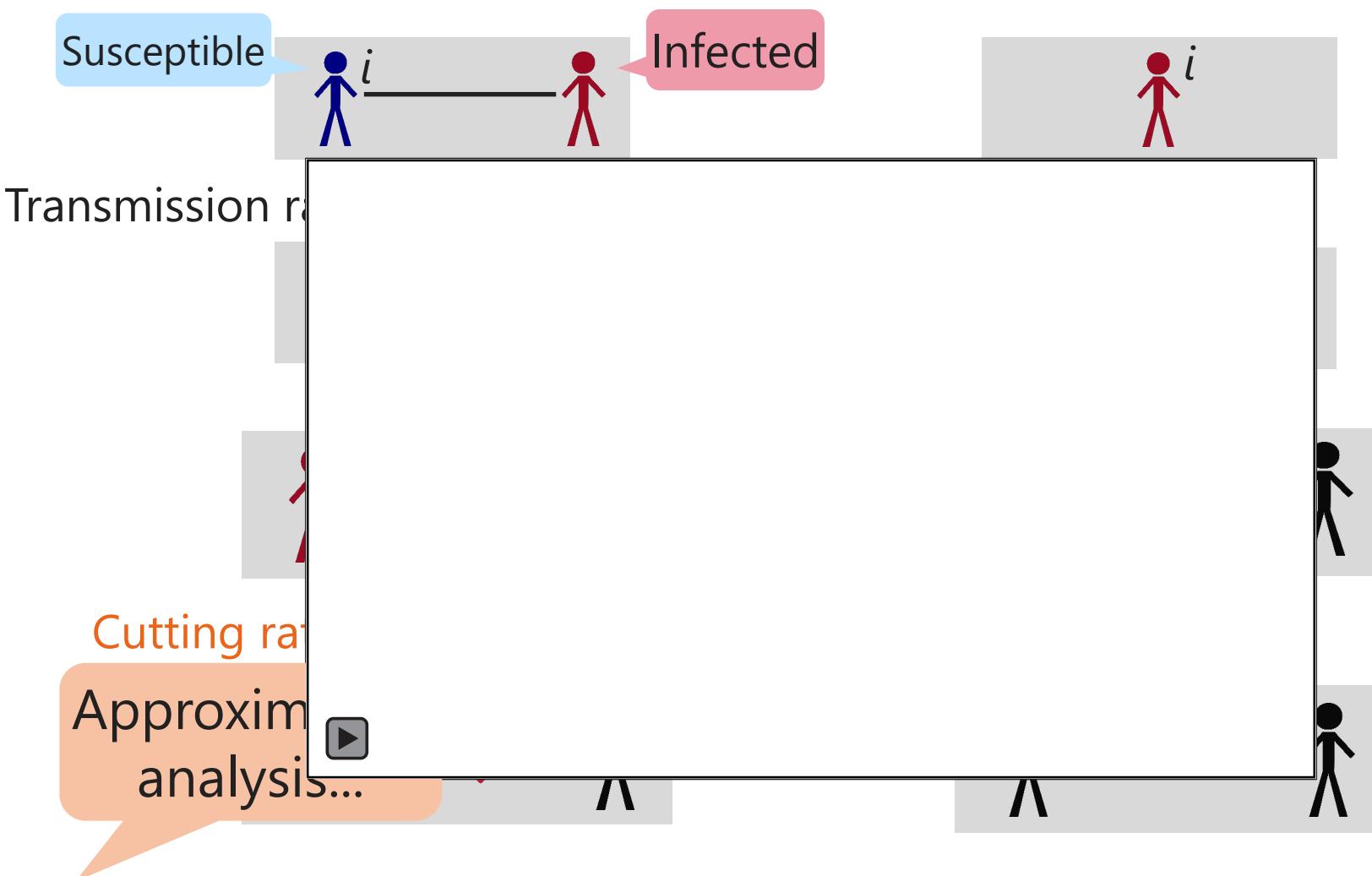
Pastor-Satorras et al., “Epidemic processes in complex networks,” *Reviews of Modern Physics*, 2015.



SIS model w/ social distancing

Adaptive SIS model

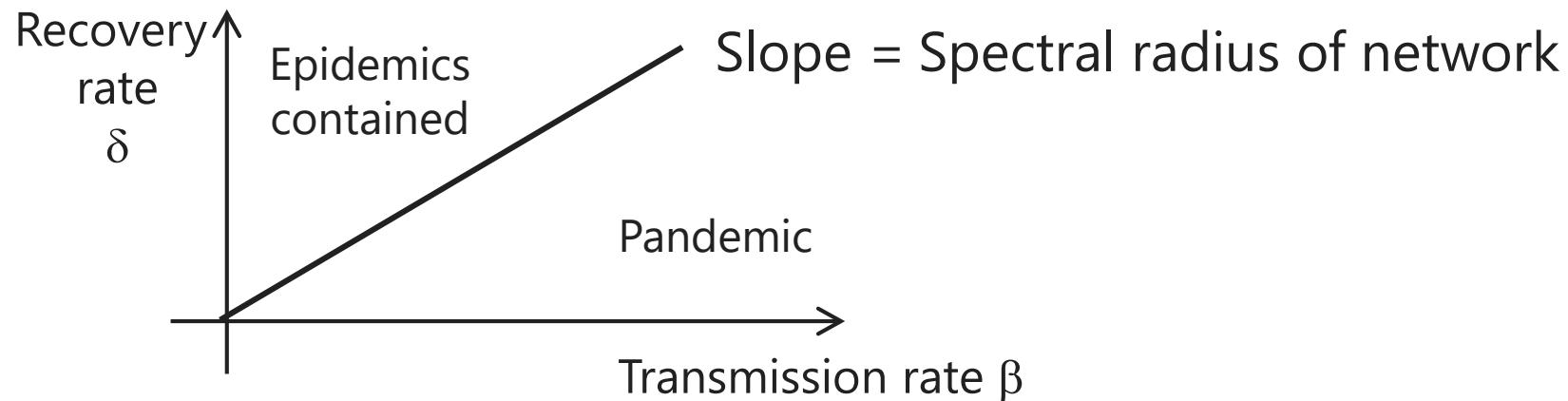
19



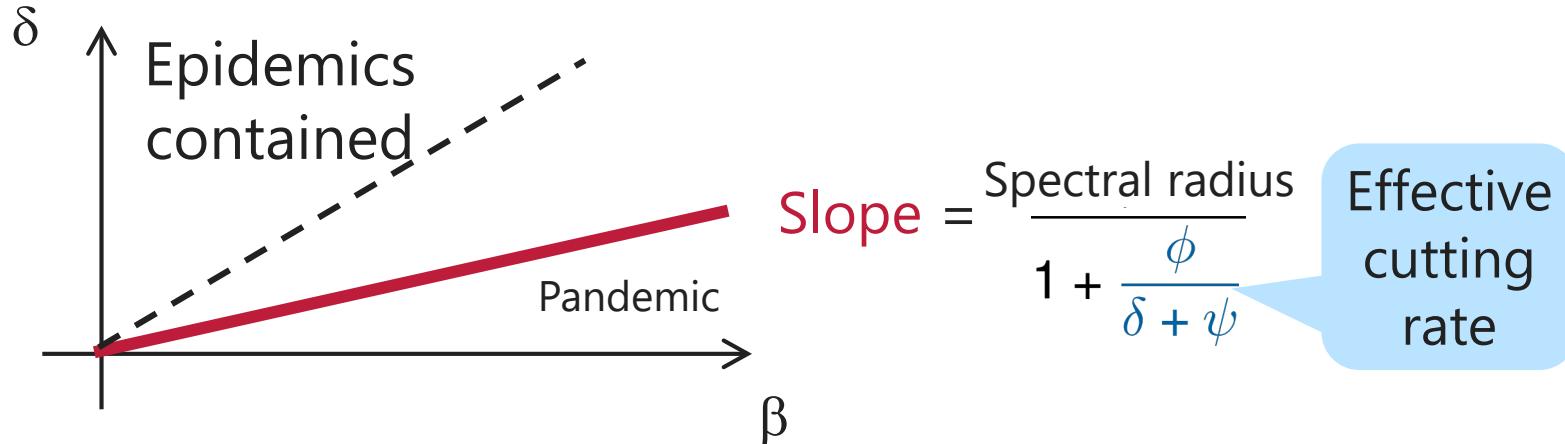
Guo et al., "Epidemic threshold and topological structure of susceptible-infectious-susceptible epidemics in adaptive networks," *Physical Review E*, 2013.

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

SIS model



Adaptive SIS model



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

Achterberg, Dubbeldam, Stam, and Van Mieghem, "Classification of link-breaking and link-creation updating rules in susceptible-infected-susceptible epidemics on adaptive networks," *Physical Review E*, 2020

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 $a_{ij} \in \{0, 1\}$

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

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

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

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

- Karate network
 - homogeneous infection, recovery, reconnection rates

- Critical cutting rate ϕ^* computed
 - Higher cutting rate leads to containment, while lower rate to pandemic

Cutting insufficient ($\phi = \phi^*/10$) Sufficiently fast cutting ($\phi = 2\phi^*$)



Disease eradication

↔
Trade-off

Keeping societal
functions

■ Question:

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

■ Optimization problem:

$$\text{minimize } \sum_{i,j} \text{cost}(\phi_{ij})$$

$$\text{subject to } \lambda_{\max} \left(\begin{bmatrix} -D_1 & B_1 \\ \psi_1 & B_2 - D_2 - \Phi - \psi_2 \end{bmatrix} \right) < 0$$

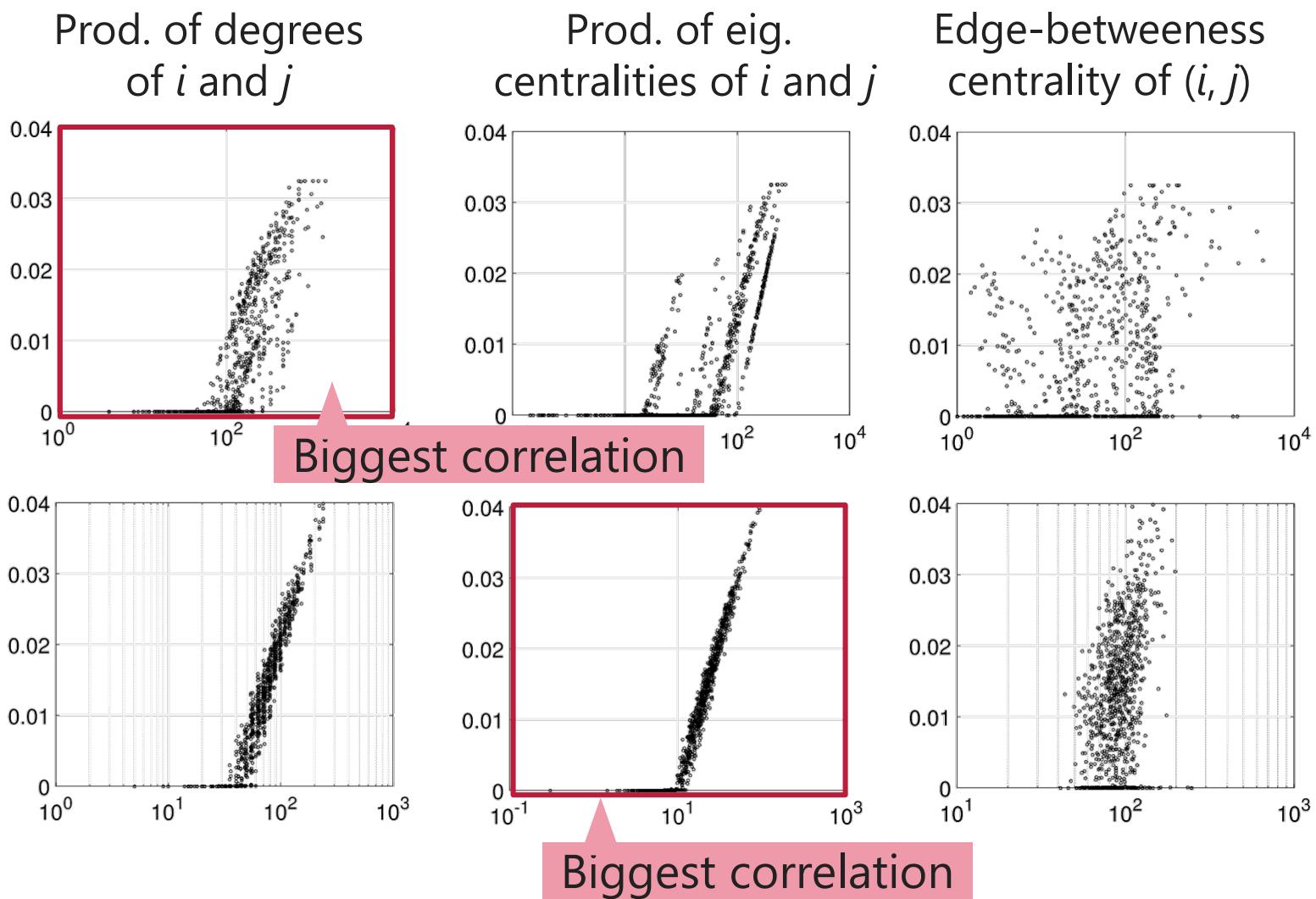
Can be equivalently converted to
a **geometric program**

Optimal social-distancing rates ϕ_{ij}

24

- Optimal cost (vertical) and centralities (horizontal)

A Facebook network



- Attempt for studying social distancing from systems and control theory
 - Society = system **to be controlled**
 - Social distancing = **controller** to be designed
- Several open research questions and technical challenges

