# Epidemic dynamics with homophily, vaccination choices, and pseudoscience attitudes

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# Motivation

# Vaccine hesitancy

Vaccines are unambiguously considered the most effective public health intervention by the scientific community

Nevertheless, **vaccine hesitancy** (and vaccination delay) is a sizable problem in many countries

- hesitancy even among educated (doctors!) depend on **trust** in institutions (Verger 2015, Lucia et al 2021)
- **information is not effective** in increasing uptake; even images or "dramatic narratives" may have **reverse** impact (Nyhan 2014, 2015. Murphy et al 2021)
- **social norms** and social networks affect vaccination behavior (Lieu 2015, Onnela 2016, Brewer et al 2017, Basili et al 2021)

So it seems that **social interactions** are crucial

# Homophily

There are two mechanisms at play here:

- diffusion of disease
- diffusion of ideas

Consider two groups: *vaxxers* and *anti–vaxxers*
(vaccine hesitancy is higher in minorities: Razai et al, 2021)

There is *homophily* in social contacts in both diffusion processes

Homophily in the first dimension can be induced by a social planner:

- countries such as US and Italy implemented **compulsory vaccination** policies to access public schools
- *Green pass* policies
- many workplaces, after Covid19, have *rotation policies*

## Our question

**Is homophily imposed by authorities, between vaxxers and anti–vaxxers, a good idea?**

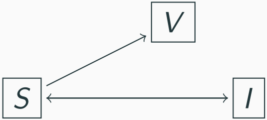
First, we study a model with exogenous choices:
imposed homophily is not good, because it slows down the recovery, if there is an outbreak of the disease

Second, we endogenize choices:
imposed homophily increases rates of vaccination and decreases share of antivaxxers. . .
. . . but the previous effect is still at play

# Literature

# Model overview

- **SI dynamics** with vaccination, for the epidemics (e.g. seasonal flu, Covid19. . . )



- Bisin and Verdier (2001) for the cultural transmission - **replicator dynamics with endogenous fitness**:
  - two groups (“cultural traits”), *a* for “anti-vax”, and *v* for “vax”;
  - “anti-vax” have a **bias**:
    they **overestimate** the cost of vaccination
    (can do the same with underestimation of cost of being ill)
  - Agents exert effort to transmit their cultural trait (**proselitism**)

# Literature

We contribute to the economics literature on endogenous epidemics and immunization:

- with respect to the literature on strategic immunization (Galeotti and Rogers 2013, Goyal and Vigier 2015):
    - we focus on the speed of recovery;
    - we study the effects of a **bias** in meeting opportunites;
    - we endogenize group structure through cultural transmission.
- with respect to cultural transmission literature on networks (e.g. Panebianco and Verdier 2015) and the literature on information diffusion (Merlino et al, 2022), we include explicitly the **epidemics**

Some works outside economics study similar dynamics, but numerically and with different purposes: Pananos et al (2017).

# Epidemic model – Exogenous choices

# Basic ingredients

- Continuum of agents, of mass 1;
- continuous time;
- two groups: $a$ and $v$;
- $q \in [0,1]$ is the rate of $a$–types
- homophilous bias $h \in [0,1]$, so that opportunities of meeting own types are respectively

$$h + (1-h)q \quad \text{and} \quad h + (1-h)(1-q) \quad ;$$

- $x_a, x_v \in [0,1]$ are the rates of vaccination, with $x_a < x_v$;
- $\mu > 0$ is the recovery rate.

## Dynamics

The rates of infection are $\rho_a$ and $\rho_v$

We have $(\rho_a, \rho_v) \in [0, 1 - x_a] \times [0, 1 - x_v]$

The system is:

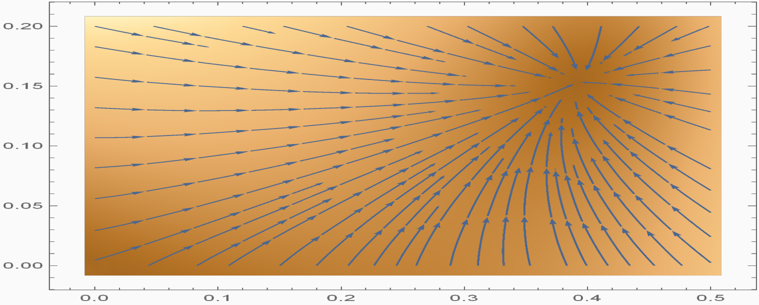
$$\begin{aligned}
\dot{\rho}_a &= ((1-\rho_a) - x_a)\Big((h + (1-h)q)\rho_a + (1-h)(1-q)\rho_v\Big) - \rho_a\mu \\
\dot{\rho}_v &= ((1-\rho_v) - x_v)\Big((h + (1-h)(1-q))\rho_v + (1-h)q\rho_a\Big) - \rho_v\mu \quad .
\end{aligned}$$

This is a non–linear dynamical system

The steady states can be solved analytically

# Low $\mu$: Endemic disease

If $\mu$ is *low* there is a unique interior steady state of the disease



The disease is endemic

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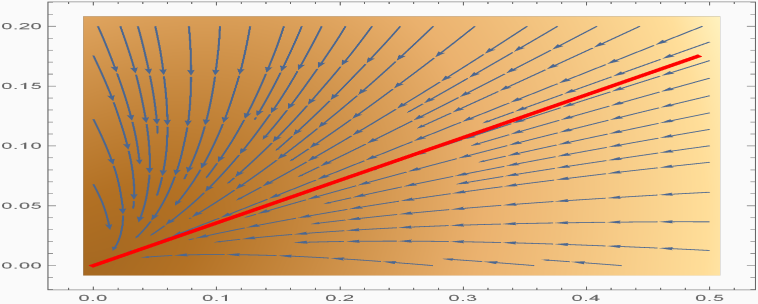
# High $\mu$: no disease in equilibrium

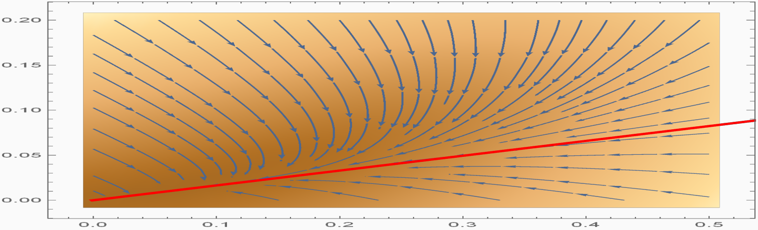
If $\mu$ is *high* the unique stable steady state is $(0, 0)$



We will focus on this second case

# Externalities, cumulative infection. . .

The dynamics can be very interesting



In the paper, we compute analytically

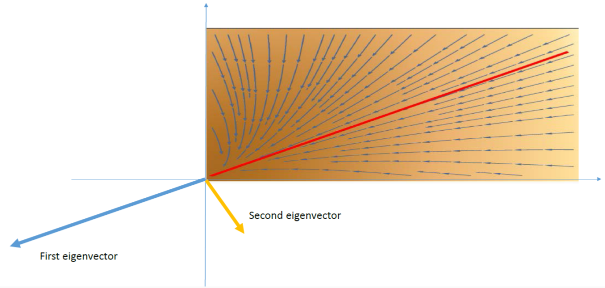
- externalities between the two groups
- cumulative infection
- the objective function of a myopic policy maker

In this talk, we focus on comparative dynamics with respect to $h$

# The role of eigenvectors and eigenvalues

We make spectral analysis of the Jacobian of the system, around the $(0,0)$ steady state

Eigenvalues are real (*hyperbolic system*)

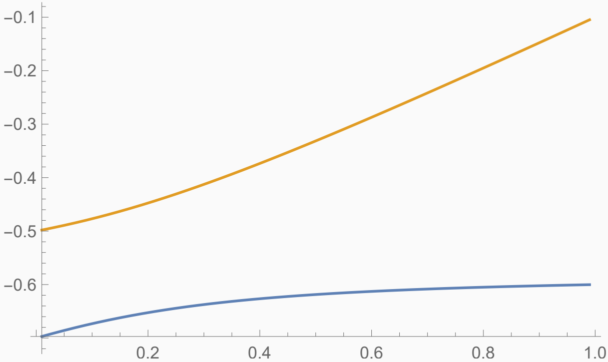


Both affect the speed of recovery

Only the second affects asymptotic convergence

# The effect of *h*

The magnitude of both eigenvalues is always decrasing in *h*



So, increasing *h* we decrease the speed of recovery from shocks

# Vaccination choices

# People compare expected costs

Members of both groups compare two costs

- **vaccination costs** are distributed uniformly between 0 and 1 among vaxxers, and between $d$ and $1 + d$ among anti–vaxxers
- $d$ is positive and it is the bias in cost perception between vaxxers and anti–vaxxers;
- people perceive the **risk of infection** as the fraction of unvaccinated people that they meet, multiplied by a factor $k$
- $k$ is positive and it represents the perceived damage from the disease, which is the same for the two groups.

$d$ is the only difference between the two groups

# Risk of infection

For a vaxxer, the fraction of unvaccinated people that she meets is

$$\sigma_v = (h + (1-h)(1-q))(1-x_v) + (1-h)q(1-x_a) \quad .$$

So:

$$x_v^* = \min\{k\sigma_v, 1\} \quad .$$

For an anti–vaxxers we have

$$\sigma_a = (h + (1-h)q)(1-x_a) + (1-h)(1-q)(1-x_v) \quad .$$

So:

$$x_a^* = \max\{0, \min\{k\sigma_a - d, 1\}\} \quad .$$

# Endogenous groups – Interior solution

# Timing

People anticipate the epidemic model,
then, based on the parameter of cultural transmission (we'll see $\alpha$), on expected $x_a^*$ and $x_v^*$, and on $h$, people decide to be anti–vaxxer or vaxxer: $q^*$

$$\Downarrow$$

Then, anticipating the epidemic model,
based on parameters of the disease $d$ and $k$, on realized $q^*$, and on $h$, people decide to vaccinate or not: $x_a^*$ and $x_v^*$

$$\Downarrow$$

The epidemic model (based on $h$, $q^*$, $x_a^*$, $x_v^*$ and $\mu$) applies,
and it rests in (0.0)

**Comparative statics and dynamics:**

The policy maker can play with $h$ to reduce $q^*$, to increase vaccination rates and to control outbreaks (i.e. shocks) in the epidemic model

# Utilities

Here we assume $d < \min\left\{\frac{1}{k^2}, \frac{k}{k+1}\right\}$

The expected (dis)utility for vaxxers, as they perceive it, is

$$U_{v\to v} = -\int_0^{k\cdot\sigma_v} c\ dc - \int_{k\cdot\sigma_v}^{1} (k\cdot\sigma_v)\ dc \quad ,$$

while for antivaxxers it is

$$U_{a\to a} = -\int_0^{k\cdot\sigma_a - d} (c+d)\ dc - \int_{k\cdot\sigma_a - d}^{1} (k\cdot\sigma_a)\ dc \quad .$$

# Others' utilities

Each group has also the perception of the disutility of the other group.

For a vaxxer the disutility of an antivaxxer is

$$U_{v\to a} = -\int_0^{k\cdot\sigma_a - d} c\ dc - \int_{k\cdot\sigma_a - d}^{1} (k\cdot\sigma_a)\ dc \quad ,$$

while for antivaxxers the disutility of a vaxxer is

$$U_{a\to v} = -\int_0^{k\cdot\sigma_v} (c+d)\ dc - \int_{k\cdot\sigma_v}^{1} (k\cdot\sigma_v)\ dc \quad .$$

Based on this, each group perceive an advantage of their group: $\Delta_a = U_{a\to a} - U_{a\to v}$ and $\Delta_v = U_{v\to v} - U_{v\to a}$.

# Dynamical system for the endogenous $q$

**Assumption**

There is a parameter $\alpha \in \mathbb{R}$, such that:
the level of $q$ increases if and only if $\Delta_a \cdot q^\alpha > \Delta_v \cdot (1-q)^\alpha$ and it decreases if and only if $\Delta_a \cdot q^\alpha < \Delta_v \cdot (1-q)^\alpha$.

When there is equality, we have a steady state (maybe not stable)

What is $\alpha$?

- $\alpha = 0$: replicator dynamics;
- $\alpha > 0$: meeting opportunities
- $\alpha < 0$: group identity
  ($\alpha = -1$ is exactly the cultural transmission model)

## What is $q^*$?

If $\alpha > 0$ there are two stable steady states: $q^* = 0$ and $q^* = 1$

If $\alpha = 0$ there is one stable steady state: $q^* = 1$

If $\alpha < 0$ there is one interior stable steady state: $q^* \in (0, 1)$

For $\alpha < 0$ and $h \to 0$ we have $q^* = \frac{1}{2}$
(because $\Delta_a - \Delta_v \to 0$)

# What about speed of recovery?

We use

$$\left.\frac{\partial q^*}{\partial h}\right|_{h \to 0 \ \& \ q^* \to \frac{1}{2}}$$

and substitute it in the derivatives of the eigenvalues of the Jacobian
(together with endogenous $x_a^*$ and $x_v^*$)

**Result:** there is a threshold $\bar{\alpha}$ such that:
for *h small enough* and $\alpha > \bar{\alpha}$, asymptotic convergence **increases** in *h*; for *h small enough* and $\alpha < \bar{\alpha}$, asymptotic convergence **decreases** in *h*;

**Important for the policy maker**: a bit of homophily is always good only if anti–vaxxers are not too rigid
otherwise, same effect as in the exogenous case