“Steady-State Social Distancing and Vaccination”

David McAdams

with Chris Avery (Harvard Kennedy) and Frederick Chen (Wake Forest)

Toulouse Talk, Part One

May 16, 2024

Overall Plan for the Talk

Overview: Broader Research Agenda

Model & preliminaries

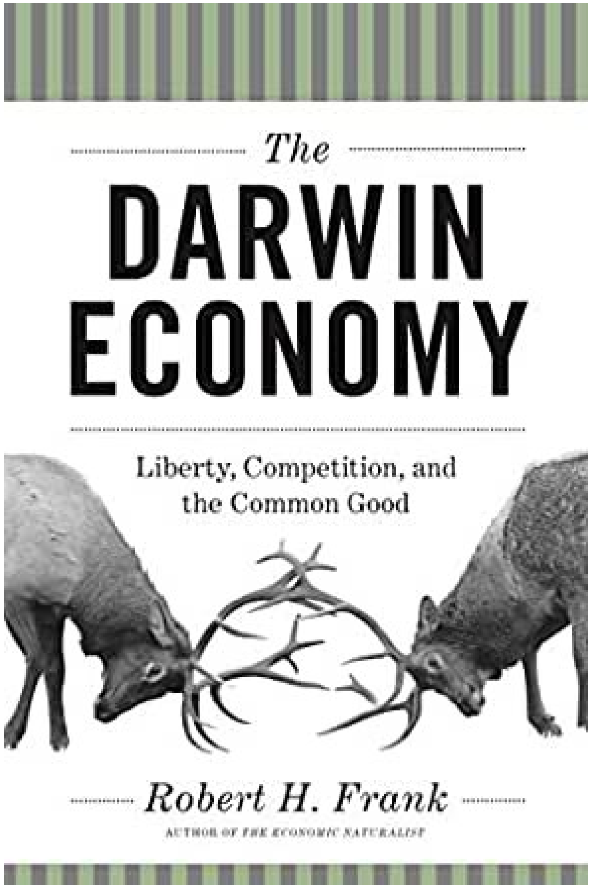
Steady-state social distancing

Steady-state vaccination

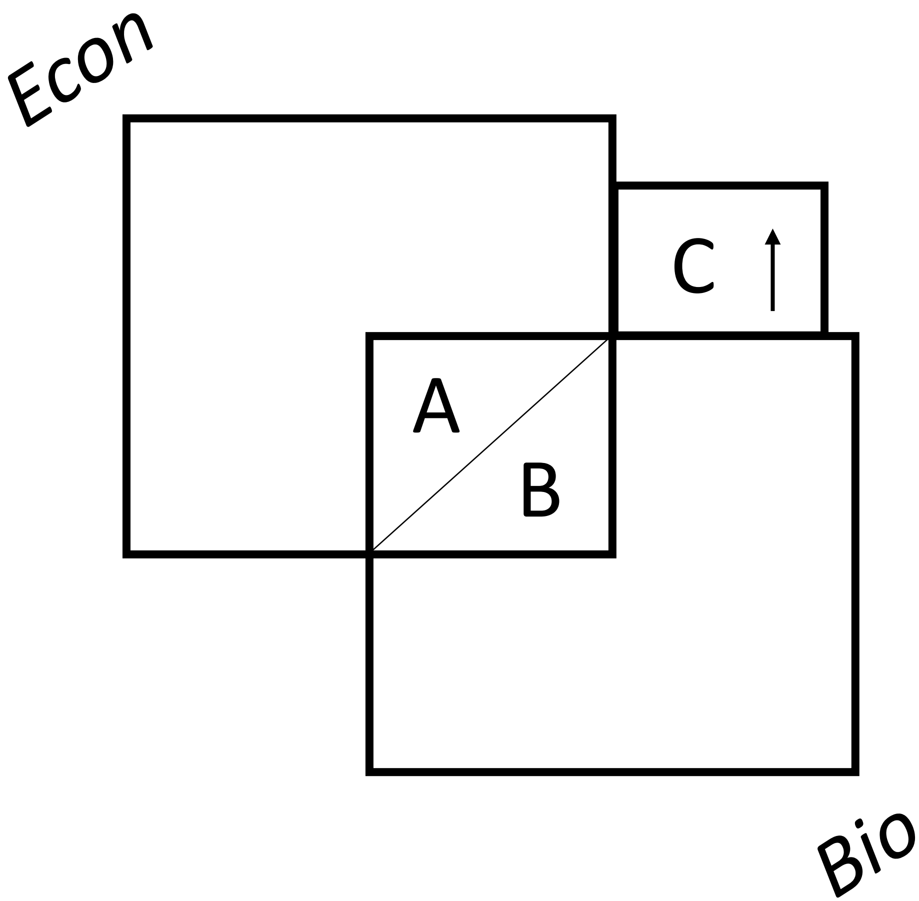
“Who was the greater economist: Adam Smith or Charles Darwin?

“The question seems absurd. Darwin, after all, was a naturalist, not an economist.

“But Robert Frank predicts that within the next century Darwin will unseat Smith as the intellectual founder of economics.” (book blurb)



Economics ⇔ Biology

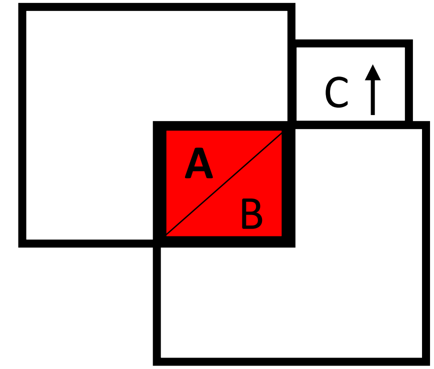


A: economic epidemiology

B: bioeconomics

C: biology-inspired economic theory

Economics ⇔ Biology



A: economic epidemiology

“Resistance Diagnosis … To Combat Antibiotic Resistance” lead author with Sam Brown (GA Tech biologist), Marc Lipsitch (Harvard epidemiologist), + postdocs, *PLoS Biology*, 2019

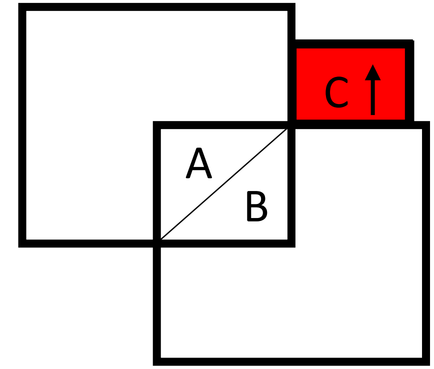
presentation “Taming Superbugs”: Duke ID Grand Rounds **2013**; GSK 2014; CDC NCEZID DHQP 2016; GA Tech Bio Science 2017; Harvard Chan 2019; TriCEM **2021**

B: bioeconomics

“The Economics of Managing Evolution” with Troy Day (Queens U biologist), David Kennedy (PSU biologist), and Andrew Read (PSU entomologist), *PLoS Biology* 2021.

presentation “The Future of Pest-Resistant Crops”: U Nebraska Lincoln **2014**; AgBiome **2022**

Economics ⇔ Biology

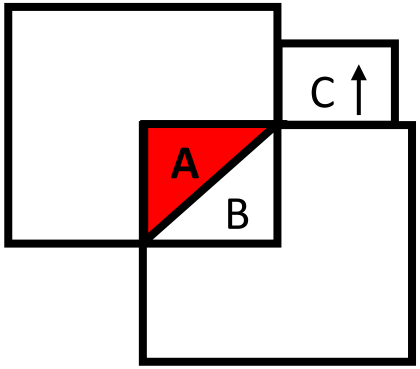


C: biology-inspired economic theory

"Adoption Epidemics and Viral Marketing" with Yangbo Song, R&R at *Theoretical Economics*

"Social Connectedness and the Market for Information" with Rachel Kranton, *AEJ: Micro* 2024

Economics ⇔ Biology



A: more economic epidemiology

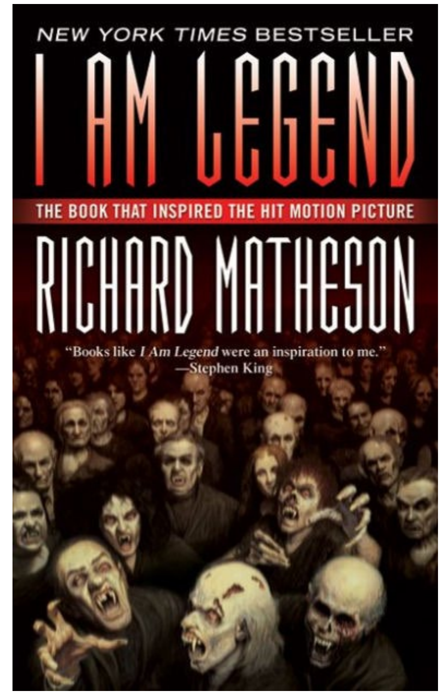
"The Blossoming of Economic Epidemiology", *Annual Review of Economics*, 2021

"Equilibrium Social Distancing during an Epidemic" with Yangbo Song and Dihan Zou, *Journal of Economic Theory*, 2023

"Steady-State Social Distancing and Vaccination" with Chris Avery & Fred Chen, *AER: Insights*, 2024

"The word **<u>'endemic'</u>** has become one of the most misused of the pandemic. … To an epidemiologist, an endemic infection is one in which **<u>overall rates are static</u>**: not rising, not falling." (cite)

Endemic Outcomes Can Be Bad!



- few zombies
- few living

- many vampires
- zero uninfected

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Model & preliminaries

- SIS model with vaccination
- steady state: epidemiological conditions
- steady state: economic conditions

Steady-state social distancing

Steady-state vaccination

Epi models: SIR vs SIS

Two workhorse models of infection-disease epidemiology: “SIR” and “SIS”

Susceptible-**I**nfected-**R**emoved: *if* recovery gives lasting immunity, early focus of Covid literature

- fast-moving epidemics are self-extinguishing, e.g., measles in Tahiti in 1929, 1951, and 1960

Susceptible-**I**nfected-**S**usceptible: *if* recovery gives no immunity to re-infection

- epidemics can cause substantial disease forever
- ***what can we say about (long-run) steady states?***

Epidemiological model

Unit-mass population, each of whom is either susceptible (S), infected (I), or vaccinated (V)

$$S(t) + I(t) + V(t) = 1$$

Epidemiological dynamics determined by:

$$I'(t) = \beta(1 - x(t))I(t)S(t) - (\gamma + \kappa)I(t)$$

new infections – recoveries/deaths

$$V(t) = V$$

Epidemiological model

$$I'(t) = \beta(1 - x(t))I(t)S(t) - (\gamma + \kappa)I(t)$$

- β*: uncontrolled transmission rate.* Each agent meets another randomly-selected agent at rate β; new infection if susceptible + infected agents meet

- $x(t)$*: susceptible social distancing*. Susceptible agents can choose to avoid fraction $x(t)$ of all meetings, reducing their infection risk

- $I(t)$: because pop'n has unit mass, $I(t)$ is the likelihood that a randomly-chosen agent is infected

→ $(1 - x(t))I(t)S(t)$ overall flow of new infections

Epidemiological model

$$I'(t) = (1 - x(t))I(t)S(t) - (\gamma + \kappa)I(t)$$

- γ*: recovery rate.* Each infected agent returns to the susceptible state at rate γ
- κ*: death rate*. All agents die at rate r (whether infected or not) and there is an equal flow of newborns. All newborns are susceptible.

→ $(\gamma + \kappa)I(t)$ is overall flow out of infection

Steady state: epi condition

$$\boxed{I'(t) = \beta(1-x)IS - (\gamma+\kappa)I = 0}$$

EITHER $I = 0, S = 1 - V$, and $x \geq \bar{x} \equiv 1 - \frac{\gamma+\kappa}{\beta(1-V)}$

[disease eliminated in steady state]

OR $I > 0, S = 1 - I - V$, and $x = x_{SS}(I) < \bar{x}$, *where*

$$\boxed{x_{SS}(I) \equiv 1 - \frac{\gamma+\kappa}{\beta(1-I-V)}}$$

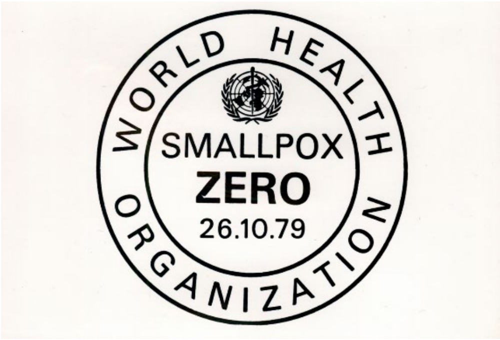
Elimination vs Eradication

Elimination means that infection is rare

- health impacts of an eliminated disease are obviously negligible, but …
- maintaining elimination may have large economic and social costs, e.g. China’s zero-COVID policy

Eradication means that the pathogen is gone

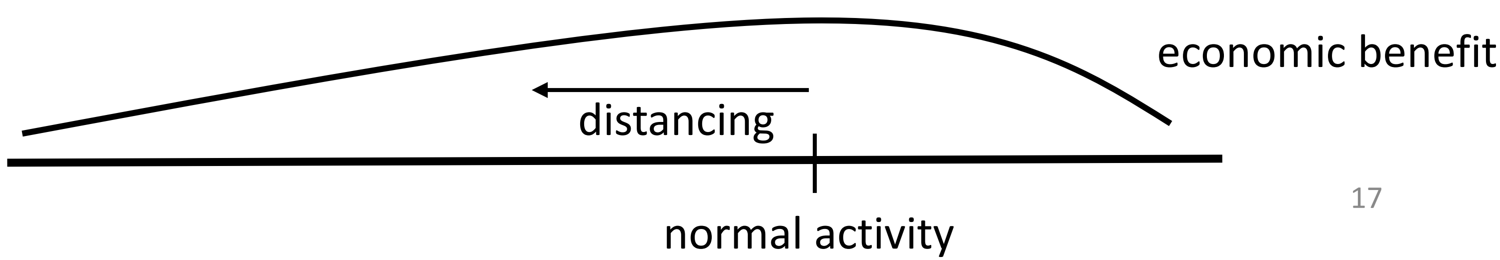
- often not possible
- e.g. if there are animal reservoirs



Economic model

Each agent seeks to minimize their expected lifetime costs due to disease *and* economic loss

- D*: disease cost.* Each infected agent incurs flow cost D due to the symptoms of infection
- $C(x)$*: social-distancing cost*. A susceptible agent who chooses social-distancing intensity $x \in [0,1]$ incurs flow cost $C(x)$
  - assumptions: $C(0) = 0, C'(0) = 0, C''(x) > 0$



Steady state: econ condition

Suppose that susceptible agents *believe* that $I(t) = I$ for all t. Let $x^*(I)$ be the individually-optimal social-distancing intensity given this belief.

The steady state with infection prevalence I is an **equilibrium steady state** if and only if

$$x^*(I) = x_{SS}(I)$$

Prop 1: *There is a unique steady-state equilibrium.*

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Model & preliminaries

Steady-state social distancing

- “baby” version of the model w/out distancing
- uniqueness of eqm steady state [Prop 1]
- equilibrium comparative statics
- when is eradication socially optimal?

Steady-state vaccination

Baby version of the model

Suppose for a moment that distancing and vaccination are both impossible.

The steady-state condition becomes

$$[I'(t) = \beta IS - (\gamma + \kappa)I = 0] \Rightarrow S^* = \frac{\gamma + \kappa}{\beta} = 1 - I^*$$

Let U_S^* and U_I^* be expected (future) lifetime costs of a susceptible and infected agent, respectively.

Becoming infected increases lifetime costs by $U_I^* - U_S^*$

Baby version of the model

While susceptible, agents in steady state:

- incur zero flow cost
- die at rate κ
- become infected at rate βI^*
- become infected at least one more time before death with likelihood $p_{S\to I}$, given by

$$p_{S\to I} = \frac{\beta I^*}{\beta I^* + \kappa}$$

Thus,

$$\boxed{U_S^* = \frac{\beta I^*}{\beta I^* + \kappa} U_I^*}$$

Baby version of the model

While infected, agents in steady state:

- incur flow cost D
- die at rate κ
- recover at rate γ
- remain infected for average duration $\frac{1}{\gamma+\kappa}$
- recover at least one more time before death with likelihood $p_{I\to S}$, given by

$$p_{I\to S} = \frac{\gamma}{\gamma+\kappa}$$

Thus,

$$\boxed{U_I^* = \frac{D}{\gamma+\kappa} + \frac{\gamma}{\gamma+\kappa} U_S^*}$$

Baby version of the model

Solving this system yields:

$$\boxed{U_I^* = \frac{D}{\kappa} \times \frac{\beta I^* + \kappa}{\beta I^* + \kappa + \gamma}}$$

$$U_S^* = U_I^* \times \frac{\beta I^*}{\beta I^* + \kappa}$$

$$U_I^* - U_S^* = \frac{D}{\beta I^* + \kappa + \gamma}$$

- Average lifetime is $\frac{1}{\kappa}$; so, $\frac{D}{\kappa}$ is expected lifetime cost if no recovery at all
- If recovery rate γ is very high, currently-infected agents will spend most of their life uninfected

Baby version of the model

Solving this system yields:

$$U_I^* = \frac{D}{\kappa} \times \frac{\beta I^* + \kappa}{\beta I^* + \kappa + \gamma}$$

$$U_S^* = U_I^* \times \frac{\beta I^*}{\beta I^* + \kappa}$$

$$\boxed{U_I^* - U_S^* = \frac{D}{\beta I^* + \kappa + \gamma}}$$

- If infection risk βI^* is high, infection *tomorrow* is likely and there's little point in preventing infection *today*
- If recovery rate γ is high, infection won't last long

Baby version of the model

Benefit of distancing in baby model: Marginally increasing social distance by $\mathrm{d}x$ reduces rate at which susceptible agent becomes infected by $\beta I^* \mathrm{d}x$

$$\text{Marginal benefit of distancing} = \beta I^* (U_I^* - U_S^*)$$

Benefit of vaccination in baby model: Once someone is vaccinated, they incur zero future costs (because, by simplifying assumption, the vaccine is perfect).

$$\text{Benefit of vaccination} = U_S^*$$

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- **uniqueness of eqm steady state** [Prop 1]
- equilibrium comparative statics
- when is eradication socially optimal?

Steady-state vaccination

Equilibrium steady state [fixed V]

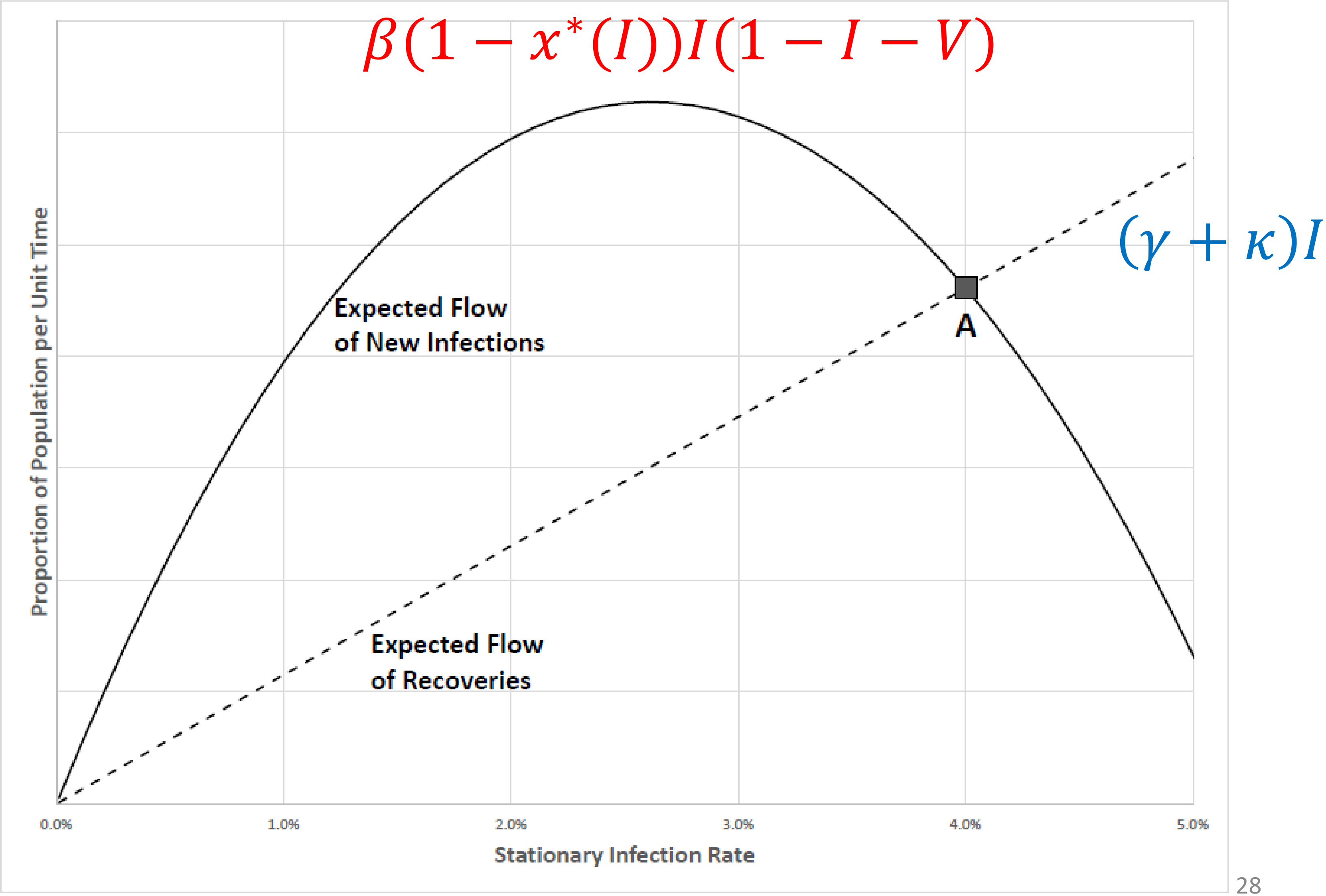
$$x^*(I) = x_{SS}(I)$$

Prop 1: *There is a unique steady-state equilibrium.*

Proof by "single-crossing" of $x^*(I)$ and $x_{SS}(I)$:

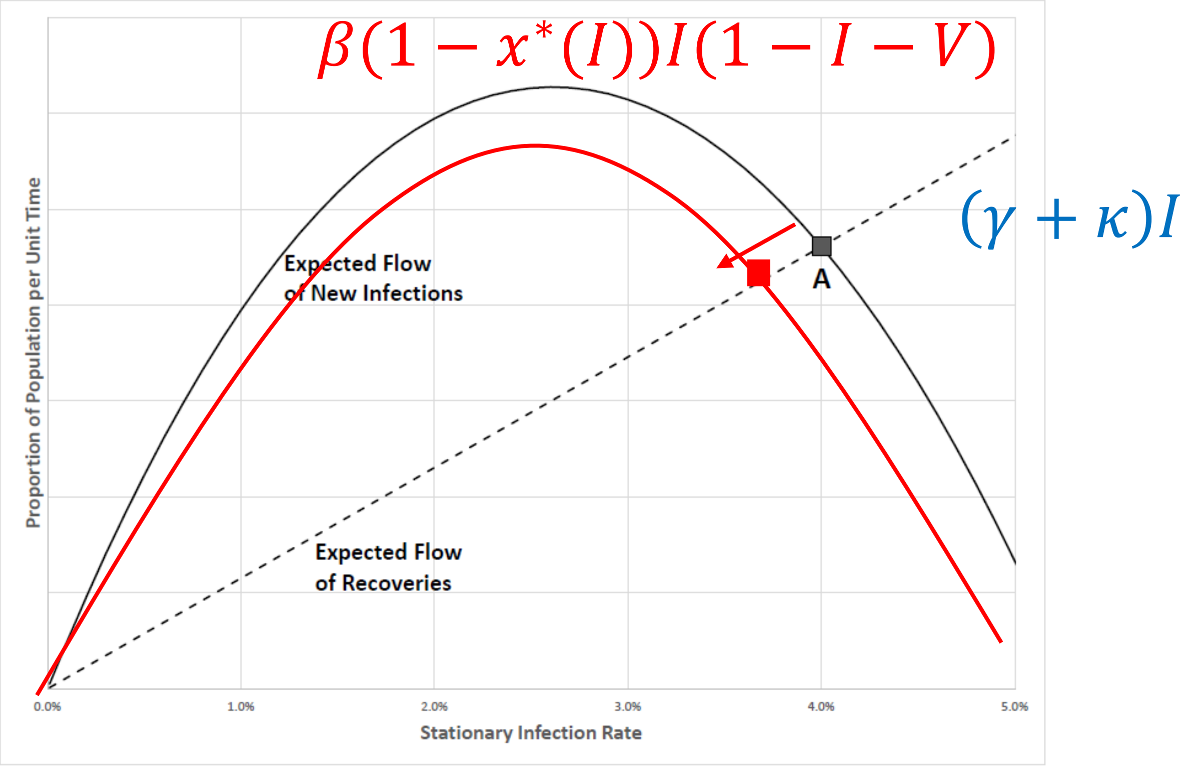
- $x^*(0) = 0 < x_{SS}(0)$
- $x^*(\bar{I}) > 0 = x_{SS}(\bar{I})$, where $\bar{I}$ is steady-state infection prevalence if no one distances at all
- $x_{SS}(I)$ *is decreasing in* I [obvious]
- $x^*(I)$ *is increasing in* I [not obvious; *see paper*]

Equilibrium steady state [fixed V]



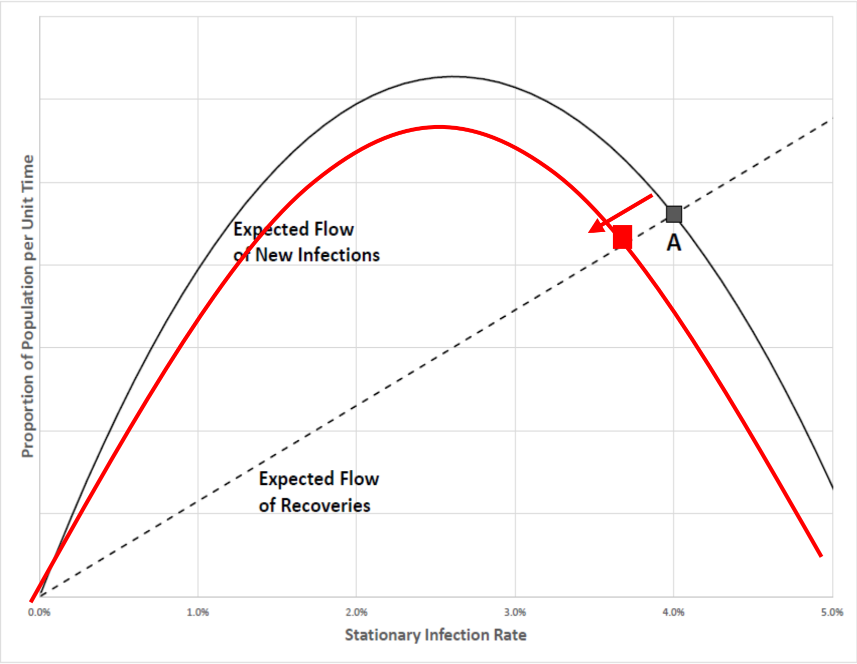
Equilibrium steady state [fixed V]

Suppose vaccination V increases → flow of new infections falls → eqm infection prevalence falls



Equilibrium steady state [fixed V]

Suppose marginal cost $C'(x)$ decreases for all x
→ individually-optimal $x^*(I)$ increases for all I → [skipping some steps] → lower flow of new infections → eqm infection prevalence falls



Overall Plan for the Talk

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Model & preliminaries

Steady-state social distancing

- "baby" version of the model w/out distancing
- uniqueness of eqm steady state [Prop 1]
- equilibrium comparative statics
- **when is eradication socially optimal?** [Prop 2]

Steady-state vaccination

Socially-optimal social distancing

Suppose that a planner wants to minimize population-wide harm in the steady state

- can dictate social-distancing intensity x
- takes vaccination level V as given

Is it ever optimal to impose zero distancing?

Is it ever optimal to eliminate the disease?

Some preliminaries

Let $I(x)$ be the steady-state infection level if susceptible agents choose social distance x

- no distancing: $I(0) = \bar{I} \equiv 1 - V - \frac{\gamma+\kappa}{\beta}$
- elimination: $I(x) = 0$ for all $x \geq \bar{x} \equiv 1 - \frac{\gamma+\kappa}{\beta(1-V)}$
- $I(x) = 1 - V - \frac{\gamma+\kappa}{\beta(1-x)}$ for all $0 \leq x \leq \bar{x}$

Let $x(I)$ be the social-distancing intensity that supports infection level $0 < I \leq \bar{I}$

Population-wide steady-state harm

$$H(I) = C\big(x(I)\big)(1 - I - V) + DI$$

social-distancing cost + disease cost

Let $\hat{I} = \arg\min_{I} H(I)$

Prop 2: (i) $\hat{I} < I^*$; (ii) $\hat{I} = 0$ iff $C'(\bar{x}) < \frac{\gamma+\kappa}{\beta(1-V)}$

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Steady-state social distancing

Steady-state vaccination

- uniqueness of eqm steady state [Prop 3]
- impact of vaccine subsidies, social-distancing subsidies, and vaccine mandates

Steady state with vaccination

Defn: A **steady-state equilibrium with endogenous vaccination** is characterized by infection level I^*, susceptible-agent social distancing x^*, and vaccination level V^* such that:

1. steady state: $\beta(1 - x^*)(1 - I^* - V^*) = \gamma + \kappa$
2. individually-optimal social distancing x^*
3. fraction V^* of newborns find it optimal to become vaccinated, i.e., $F\left(U_S^*(I^*)\right) = V^*$

Prop 3: *There is a unique steady-state equilibrium with endogenous vaccination.*

Steady state with vaccination

$D_V(I)$: demand for vaccination, i.e., $D_V(I) = F(U_S^*(I))$

- fraction of newborn agents who choose to be vaccinated
- easy to check: $D_V(I)$ is increasing in infection level I

$SS_V(I)$: vaccination level that induces $I^*(V) = I$

- we previously showed that steady-state equilibrium infection prevalence $I^*(V)$ is decreasing in V
- so, $SS_V(I)$ is decreasing in I

The unique crossing point of these curves corresponds to the unique steady-state equilibrium with endogenous vaccination.

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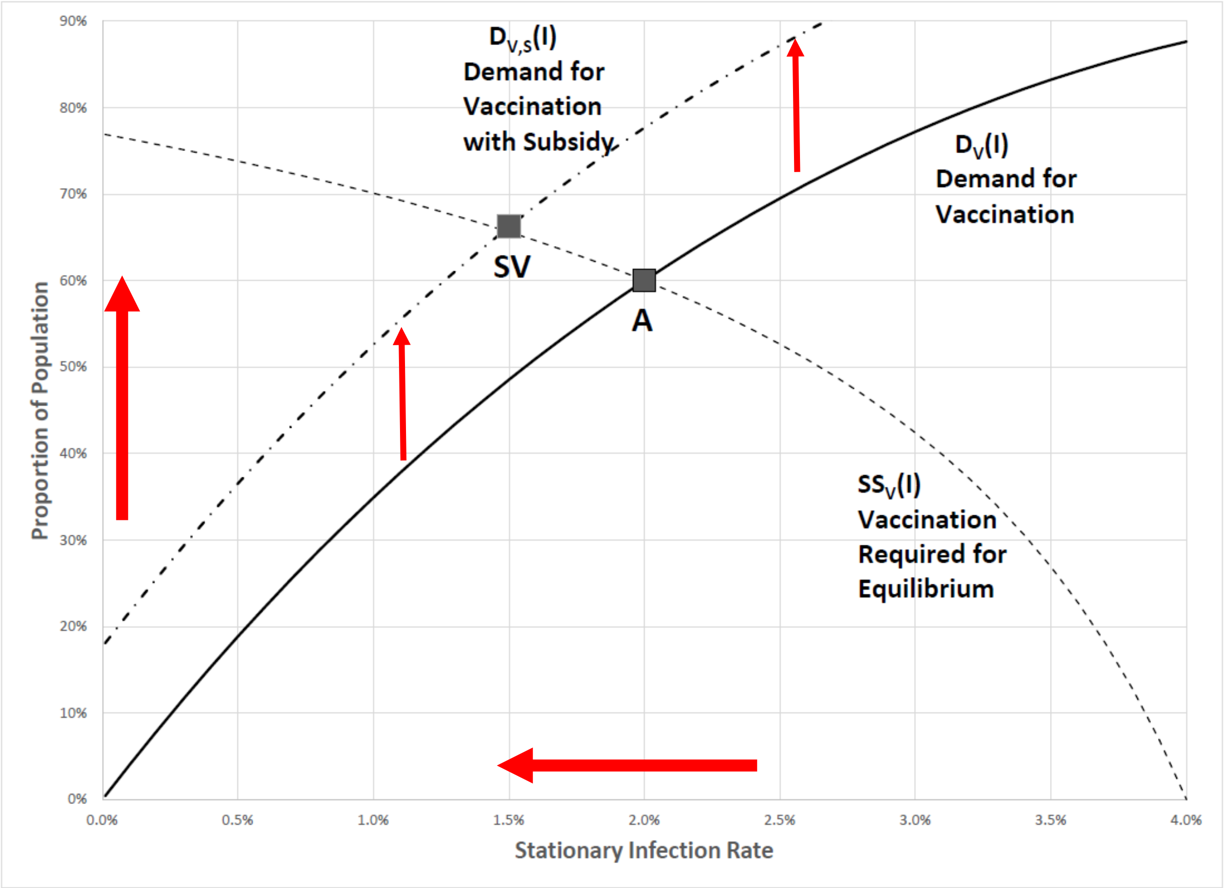
Steady-state social distancing

Steady-state vaccination

- uniqueness of eqm steady state [Prop 3]
- **impact of vaccine subsidies, social-distancing subsidies, and related policies**

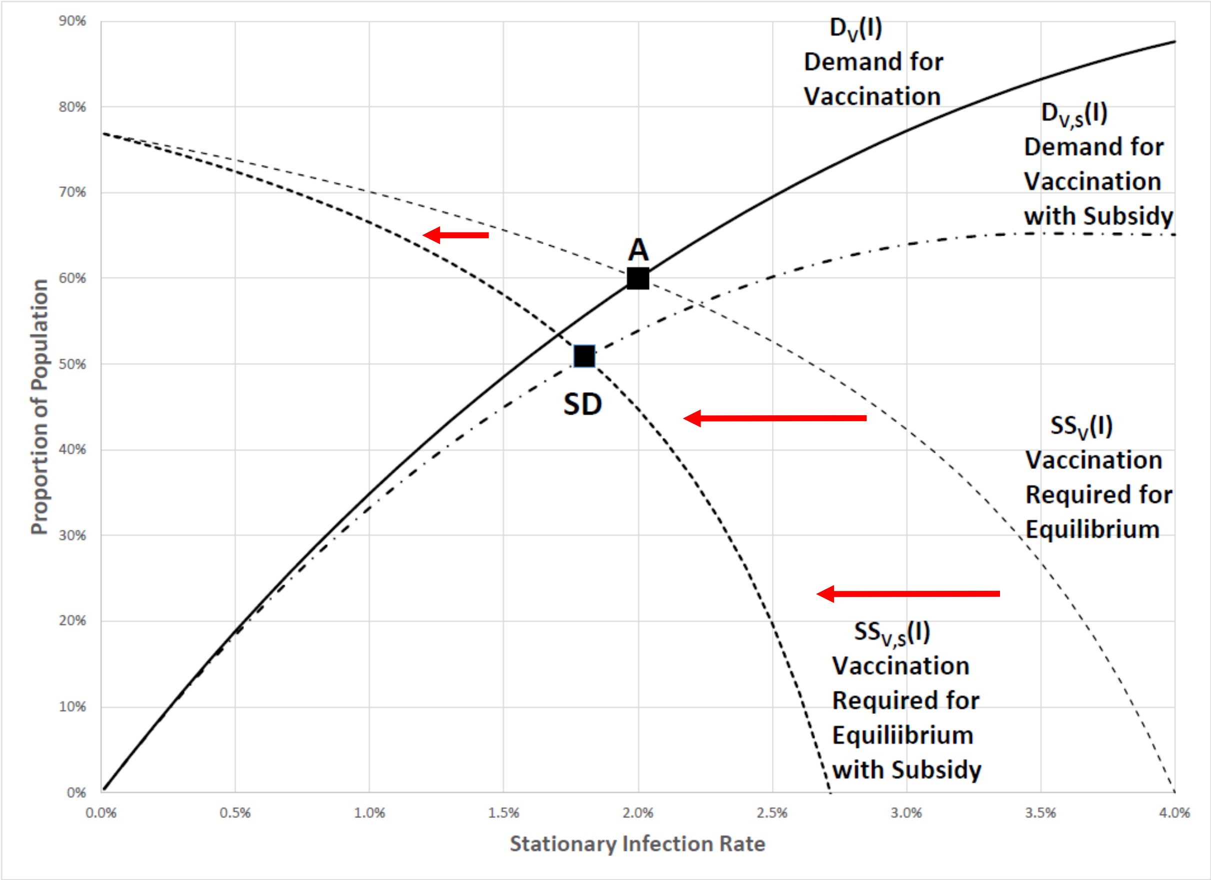
Effect of a Vaccine Subsidy



– lowering the cost of vaccination increases demand

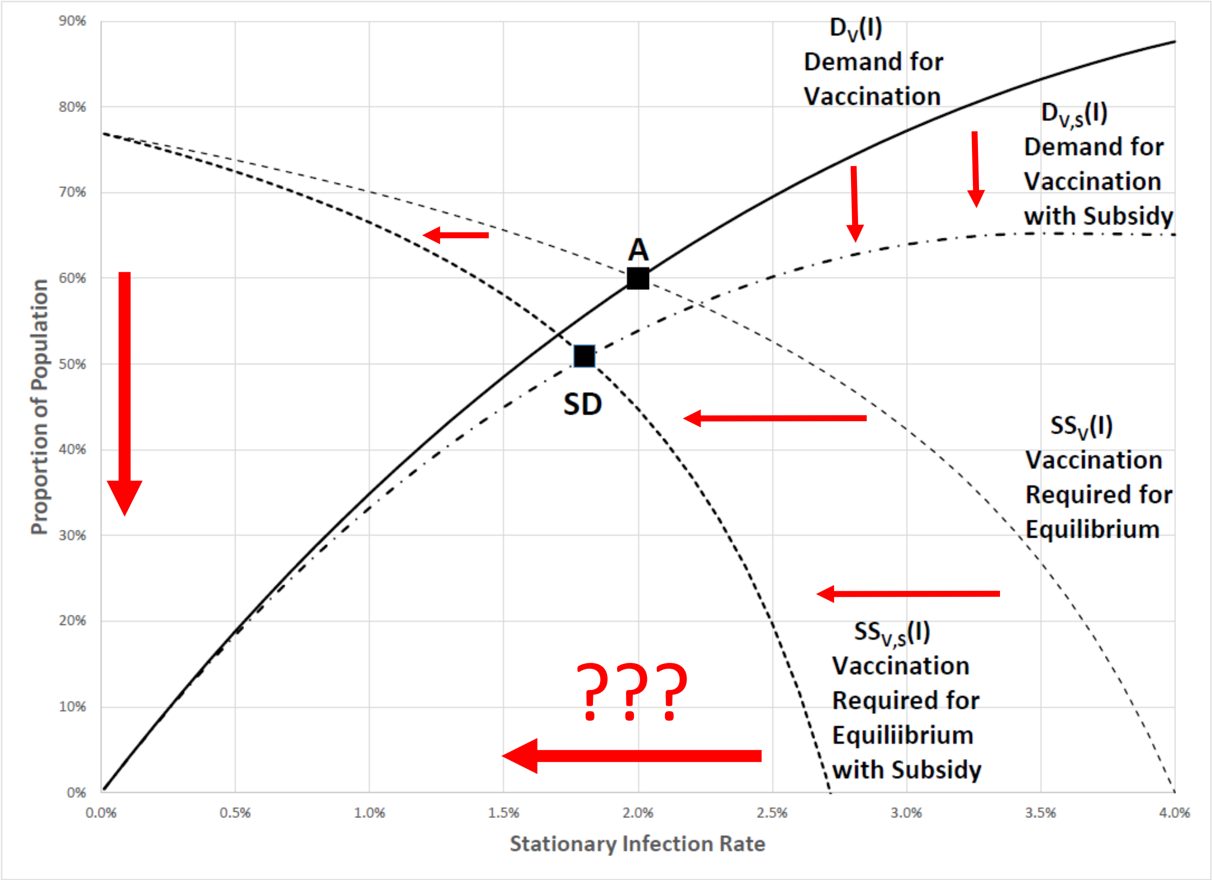
→ *more vaccination* and *less infection*

Effect of a Distancing Subsidy: I



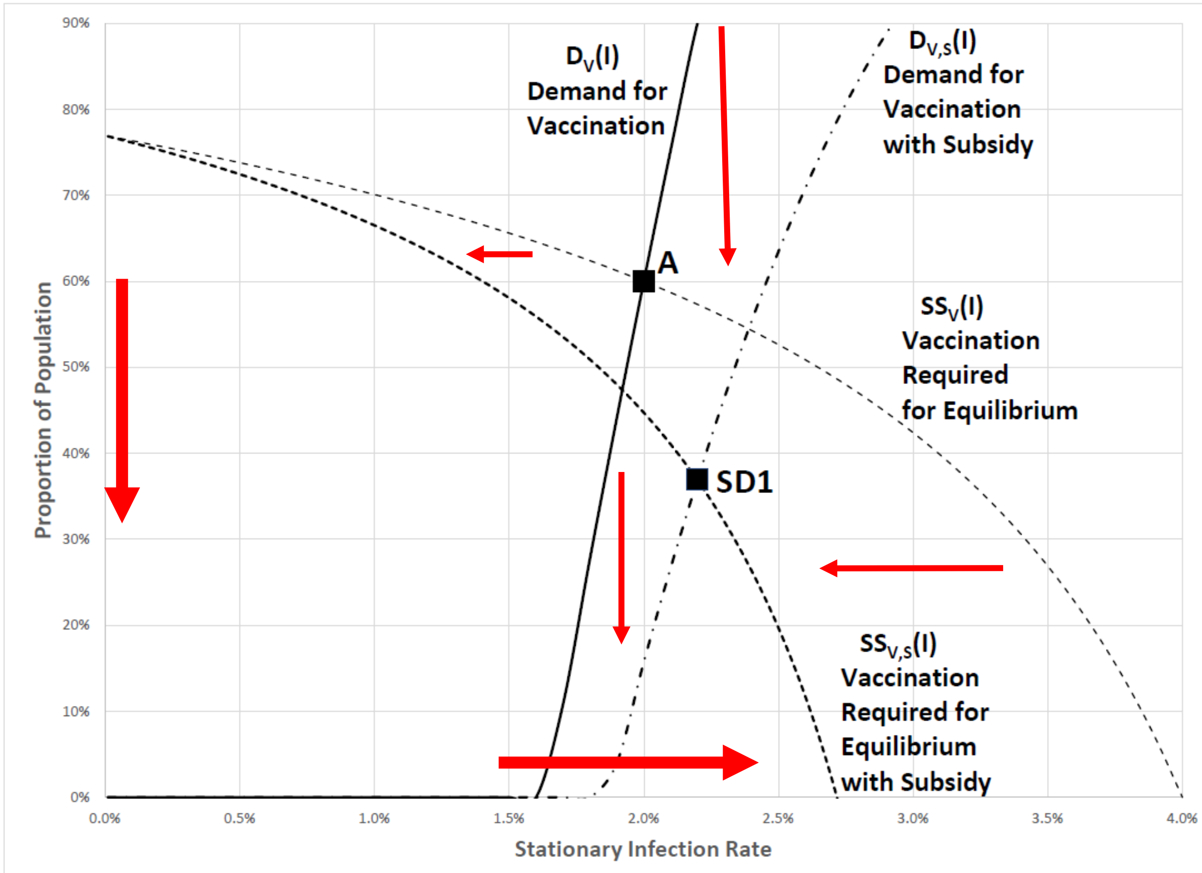
– lowering the cost of distancing reduces vaccination level needed to support any given infection level

Effect of a Distancing Subsidy: I



– … while ALSO reducing demand for vaccination
– *vaccination falls* and *ambiguous effect on infection*

Effect of a Distancing Subsidy: II



– … while ALSO reducing demand for vaccination
– *vaccination falls* and *ambiguous effect on infection*

Steady state with vaccination

In January 2022, France imposed restrictions that barred unvaccinated people from high-value low-risk spaces such as open-air cafes.

The goal of this policy was to “annoy the unvaccinated”

– Emmanuel Macron: “j'ai tres envie de les emmerder”
– Google translation: “I really want to piss them off”

But our analysis suggests a different sort of rationale.

Why “annoy the unvaccinated”?

Blocking low-value high-risk activities = imposing a minimal social-distancing intensity

- reduces vaccination needed to support each infection level when binding AND reduces demand for vaccination
- same qualitative effects as social-distancing subsidy

→ *less vaccination* and *ambiguous effect on infection*

Blocking high-value low-risk activities = imposing a tax on unvaccinated = vaccination subsidy

→ *more vaccination* and *less infection*

Summary of main contributions

Develop a **tractable econ-epi framework** with endogenous social distancing and endogenous vaccination

Highlight **simple economics** of epidemic steady states

Highlight qualitative difference between policies that promote **distancing vs vaccination**