

Biological Contagion

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Principles of Complex Systems, Vols. 1, 2, 3D, 4 Fourever, V for Vendetta

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University of Vermont | Santa Fe Institute



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The PoCSverse
Biological Contagion
1 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

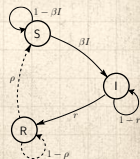
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCServe
Biological Contagion
2 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

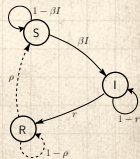
Model output

Nutshell

Other kinds of
prediction

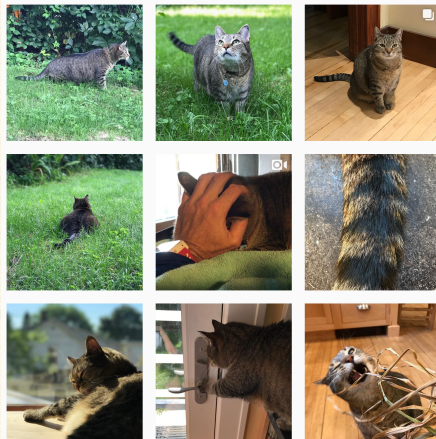
SIR is the virus

References



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The PoCVerse
Biological Contagion
3 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

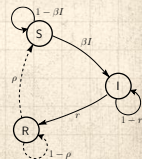
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Outline

Introduction

Simple disease spreading models

Prediction

More models

Toy metapopulation models

Model output

Nutshell

Other kinds of prediction

SIR is the virus

References

The PoCServe
Biological Contagion
4 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

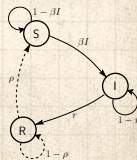
Model output

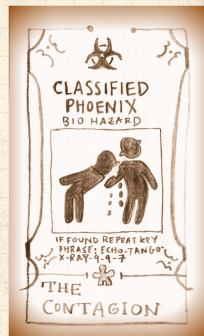
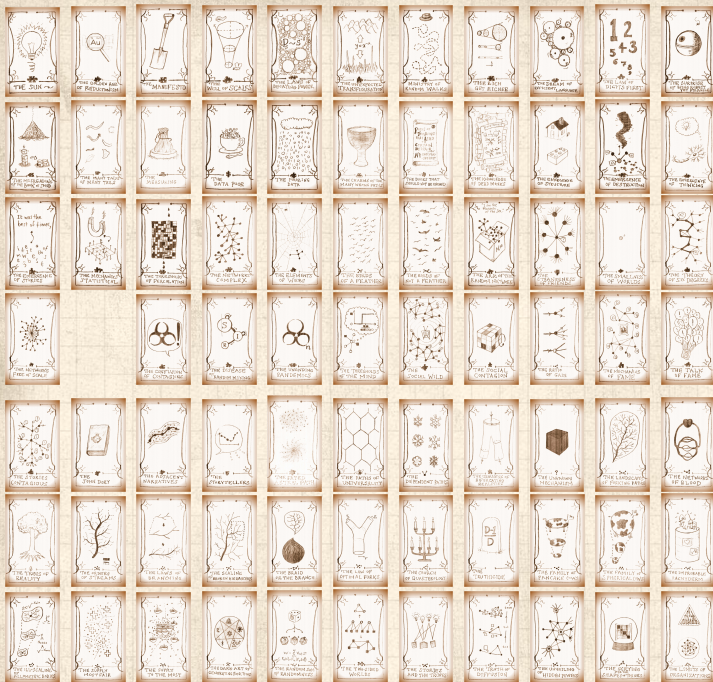
Nutshell

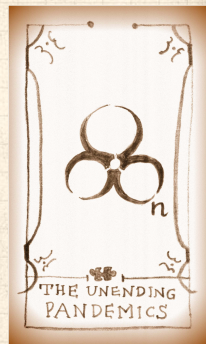
Other kinds of
prediction

SIR is the virus

References







THE UNENDING
PANDEMICS



An awful recording: Wikipedia's list of epidemics from 430 BC on.



WIKIPEDIA
The Free Encyclopedia

[Main page](#)
[Contents](#)
[Featured content](#)
[Current events](#)
[Random article](#)
[Donate to Wikipedia](#)
[Wikipedia store](#)

[Interaction](#)
[Help](#)
[About Wikipedia](#)
[Community portal](#)
[Recent changes](#)
[Contact page](#)

[Tools](#)
[What links here](#)
[Related changes](#)
[Upload file](#)
[Special pages](#)
[Permanent link](#)
[Page information](#)
[Wikidata item](#)
[Cite this page](#)

[Print/export](#)
[Create a book](#)
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[Printable version](#)

[Languages](#)
 العربية
 Deutsch
 Simple English
[Edit links](#)

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Read [Edit](#) [View history](#)

List of epidemics

From Wikipedia, the free encyclopedia

This article is a **list of epidemics of infectious disease**. Widespread and chronic complaints such as **heart disease** and **allergy** are not included if they are not thought to be infectious.

This list is incomplete; you can help by [expanding it](#).

Death toll (estimate)	Location	Date	Comment	Disease	Reference
ca. 75,000 - 100,000	Greece	429–426 BC	Known as Plague of Athens , because it was primarily in Athens.	unknown, similar to typhoid	
ca. 30% of population	Europe, Western Asia, Northern Africa	165–180	Known as Antonine Plague , due to the name of the Roman emperor in power at the time.	unknown, symptoms similar to smallpox	
	Europe	250–266 AD	Known as the Plague of Cyprian named after St. Cyprian Bishop of Carthage.	unknown, possibly smallpox	
ca. 40% of population	Europe	541–542	Known as Plague of Justinian , due to the name of the Byzantine emperor in power at the time.	Bubonic plague	[1]
30% to 70% of population	Europe	1346–1350	Known as " Black Death " or Second plague pandemic , first return of the plague to Europe after the Justinianic plague of the 6th century.	plague	[2]
5–15 million (80% of population)	Mexico	1545–1548	Cocoliztli	viral hemorrhagic fever	[3][4]
2 - 2.5 million (50% of population)	Mexico	1576	Cocoliztli	viral hemorrhagic fever	[5][6]
	Seneca nation	1592–1596		measles	[7]



Plague panel with the triumph of death. 1607–36, Deutsches Historisches Museum Berlin



An artistic portrayal of cholera which was epidemic in the 19th century

The PoCVerse
Biological Contagion
7 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

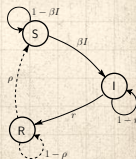
Model output

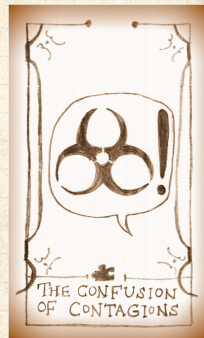
Nutshell

Other kinds of
prediction

SIR is the virus

References





THE CONFUSION
OF CONTAGIONS

Contagion

A confusion of contagions:

The PoCSverse
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

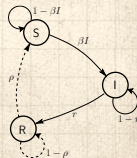
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

The PoCSverse
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

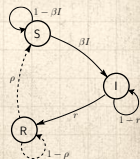
Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:

🧱 Did Harry Potter spread like a virus?



Contagion

The PoCSverse
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

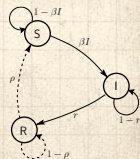
SIR is the virus

References

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Contagion

The PoCSverse
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

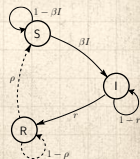
References

A confusion of contagions:

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🧱 Suicide, violence?



Contagion

The PoCserve
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

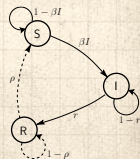
Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:

- Did Harry Potter spread like a virus?
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- Suicide, violence?
- Morality? Evil? Laziness? Stupidity? Happiness?



Contagion

The PoCServe
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:



Did Harry Potter spread like a virus?



Can disinformation be “infectious”?



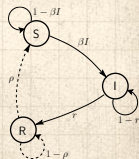
Suicide, violence?



Morality? Evil? Laziness? Stupidity? Happiness?



Religion?



Contagion

The PoCServe
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

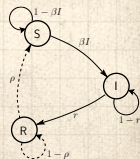
Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:

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- Can disinformation be “infectious”?
- Suicide, violence?
- Morality? Evil? Laziness? Stupidity? Happiness?
- Religion?
- Democracy ...?



Contagion

The PoCServe
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

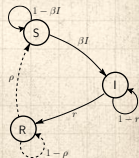
Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:

-  Did Harry Potter spread like a virus?
-  Can disinformation be “infectious”?
-  Suicide, violence?
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-  Religion?
-  Democracy ...?
-  Language? The alphabet? ^[13]



Contagion

The PoCServe
Biological Contagion
9 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

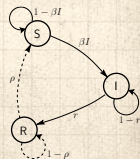
Other kinds of
prediction

SIR is the virus

References

A confusion of contagions:

-  Did Harry Potter spread like a virus?
-  Can disinformation be “infectious”?
-  Suicide, violence?
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-  Democracy ...?
-  Language? The alphabet? ^[13]
-  Stories?



Contagion

Naturomorphisms

The PoCSverse
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

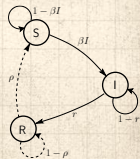
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

Naturomorphisms



“The feeling was contagious.”

The PoCSverse
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

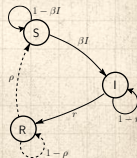
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

Naturomorphisms



“The feeling was contagious.”



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The PoCServe
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

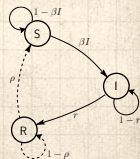
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

Naturomorphisms



“The feeling was contagious.”



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“Freedom is the most contagious virus known to man.”

—Hubert H. Humphrey, Johnson’s vice president

The PoCServe
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

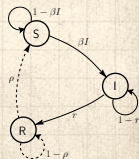
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

Naturomorphisms



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“Nothing is so contagious as enthusiasm.”

—Samuel Taylor Coleridge

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

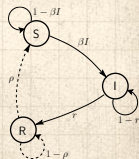
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

The PoCServe
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Naturomorphisms



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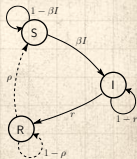


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Optimism according to Ambrose Bierce:

The doctrine that everything is beautiful, including what is ugly, everything good, especially the bad, and everything right that is wrong. ...



Contagion

The PoCServe
Biological Contagion
10 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Naturomorphisms



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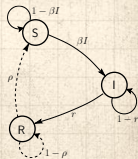


“Nothing is so contagious as enthusiasm.”

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Optimism according to Ambrose Bierce:

The doctrine that everything is beautiful, including what is ugly, everything good, especially the bad, and everything right that is wrong. ... **It is hereditary, but fortunately not contagious.**



Social contagion

Eric Hoffer, 1902–1983

There is a grandeur in the uniformity of the mass.

The PoCSverse
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

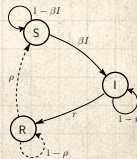
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Social contagion

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There is a grandeur in the uniformity of the mass. When a fashion, a dance, a song, a slogan or a joke

The PoCSverse
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

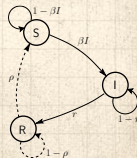
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Social contagion

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The PoCSverse
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

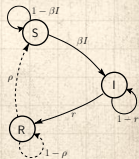
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCSverse
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

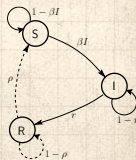
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCServe
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

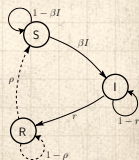
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Social contagion

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The PoCServe
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

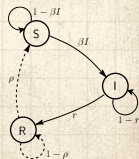
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Social contagion

The PoCServe
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

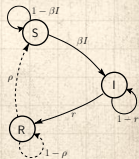
Other kinds of
prediction

SIR is the virus

References

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Social contagion

The PoCServe
Biological Contagion
11 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

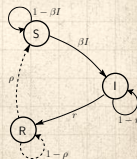
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Hoffer  was an interesting fellow...



The spread of fanaticism

Hoffer's most famous work: "**The True Believer:**
Thoughts On The Nature Of Mass Movements" (1951) ^[15]

Aphorisms-aplenty:

The PoCServe
Biological Contagion
12 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

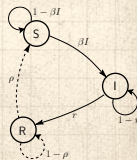
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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"We can be absolutely certain only about things we do not understand."

The PoCVerse
Biological Contagion
12 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

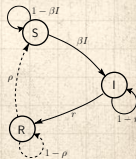
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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"Mass movements can rise and spread without belief in a God, but never without belief in a devil."

The PoCServe
Biological Contagion
12 of 93

----- Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

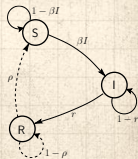
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The spread of fanaticism

Hoffer's most famous work: "**The True Believer:**
Thoughts On The Nature Of Mass Movements" (1951) ^[15]

Aphorisms-aplenty:

- “We can be absolutely certain only about things we do not understand.”
- “Mass movements can rise and spread without belief in a God, but never without belief in a devil.”
- “Where freedom is real, equality is the passion of the masses.

”

The PoCVerse
Biological Contagion
12 of 93

----- Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

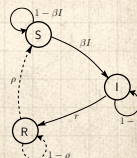
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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Aphorisms-aplenty:



"We can be absolutely certain only about things we do not understand."



"Mass movements can rise and spread without belief in a God, but never without belief in a devil."



"Where freedom is real, equality is the passion of the masses.
Where equality is real, freedom is the passion of a small minority."

----- Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

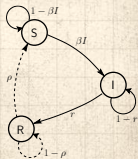
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Imitation



CONFORMITY

WHEN PEOPLE ARE FREE TO DO AS THEY PLEASE,
THEY USUALLY IMITATE EACH OTHER.

www.despair.com

despair.com

“When people are free to do as they please, they usually imitate each other.”

—Eric Hoffer

“The Passionate State of Mind” [16]

The PoCVerse
Biological Contagion
13 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

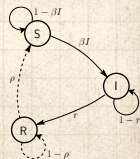
Model output

Nutshell

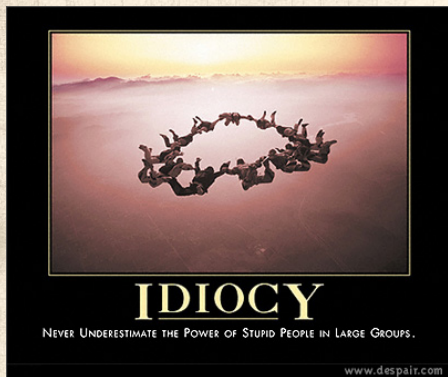
Other kinds of
prediction

SIR is the virus

References



The collective...



despair.com

“Never Underestimate the Power of Stupid People in Large Groups.”

The PoCVerse
Biological Contagion
14 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

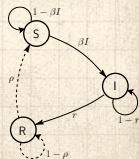
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

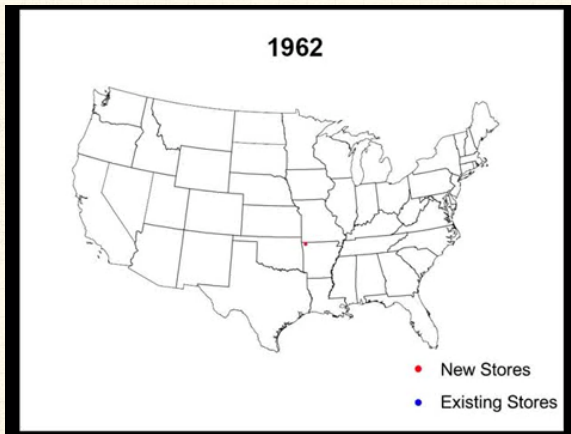
Nutshell

Other kinds of
prediction

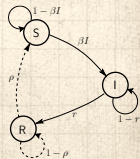
SIR is the virus

References

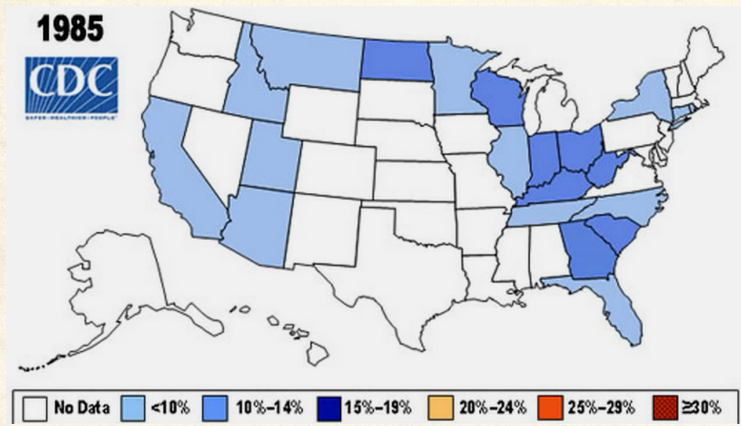
Examples of non-disease spreading:



Spreading of certain buildings in the US.



Marbleization of the US:



The spreading of spreading.

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

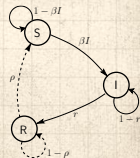
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The most terrifying contagious outbreak?

The PoCVerse
Biological Contagion
17 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

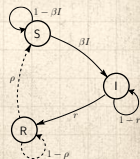
References

Google books Ngram Viewer

Graph these comma-separated phrases: ☐ case-insensitive

between and from the corpus with smoothing of

[Search lots of books](#)



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

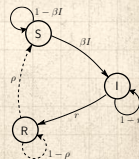
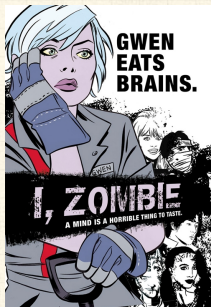
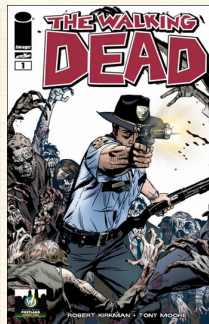
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

Definitions

The PoCSverse
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

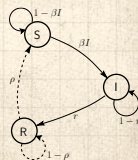
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Contagion

The PoCSverse
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

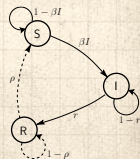
Other kinds of
prediction

SIR is the virus

References

Definitions

 (1) The spreading of a quality or quantity between individuals in a population.



Contagion

The PoCVerse
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

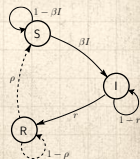
Other kinds of
prediction

SIR is the virus

References

Definitions

-  (1) The spreading of a quality or quantity between individuals in a population.
-  (2) A disease itself: the plague, a blight, the dreaded lurgi, ...



Contagion

The PoCVerse
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

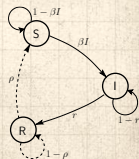
Other kinds of
prediction

SIR is the virus

References

Definitions

-  (1) The spreading of a quality or quantity between individuals in a population.
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the plague, a blight, the dreaded lurgi, ...
-  from Latin: *con* = 'with' + *tangere* 'to touch.'



Contagion

The PoCServe
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

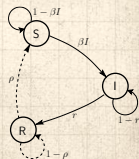
Other kinds of
prediction

SIR is the virus

References

Definitions

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- 🧱 Contagion has unpleasant overtones...



Contagion

The PoCServe
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

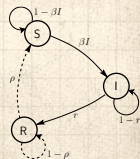
Other kinds of
prediction

SIR is the virus

References

Definitions

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- 🧱 Just **Spreading** might be a more neutral word



Contagion

The PoCServe
Biological Contagion
19 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

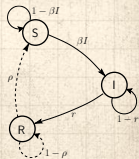
Other kinds of
prediction

SIR is the virus

References

Definitions

-  (1) The spreading of a quality or quantity between individuals in a population.
-  (2) A disease itself:
the plague, a blight, the dreaded lurgi, ...
-  from Latin: *con* = 'with' + *tangere* 'to touch.'
-  Contagion has unpleasant overtones...
-  Just **Spreading** might be a more neutral word
-  But contagion is kind of exciting...



Contagions

The PoCSverse
Biological Contagion
20 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

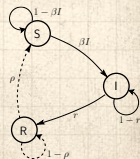
Nutshell

Other kinds of
prediction

SIR is the virus

References

Two main classes of contagion



Contagions

The PoCSverse
Biological Contagion
20 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

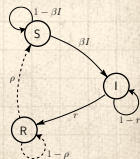
Other kinds of
prediction

SIR is the virus

References

Two main classes of contagion

1. Infectious diseases



Contagions

The PoCSverse
Biological Contagion
20 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

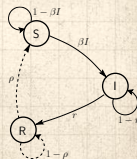
Other kinds of
prediction

SIR is the virus

References

Two main classes of contagion

1. Infectious diseases
2. Social contagion



Contagions

The PoCSverse
Biological Contagion
20 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

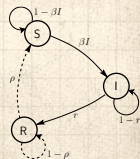
Other kinds of
prediction

SIR is the virus

References

Two main classes of contagion

1. **Infectious diseases:**
tuberculosis, HIV, ebola, SARS, influenza, zombification, ...
2. **Social contagion**



Contagions

The PoCSverse
Biological Contagion
20 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

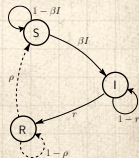
Two main classes of contagion

1. Infectious diseases:

tuberculosis, HIV, ebola, SARS, influenza, zombification, ...

2. Social contagion:

fashion, word usage, rumors, uprisings, religion, stories about zombies, ...



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

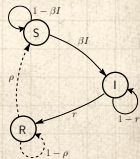
SIR is the virus

References

Archival footage from the Black Plague:



Bring out your dead.



Community—S2E06: Epidemiology



“I thought I was special”

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

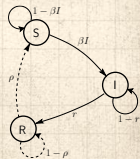
Model output

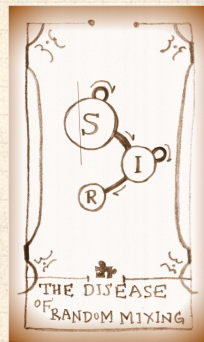
Nutshell

Other kinds of
prediction

SIR is the virus

References





Mathematical Epidemiology

The PoCVerse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

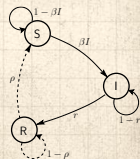
Nutshell

Other kinds of
prediction

SIR is the virus

References

The standard **SIR model** [22]



Mathematical Epidemiology

The PoCServe
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

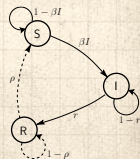
Other kinds of
prediction

SIR is the virus

References

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 = basic model of disease contagion



Mathematical Epidemiology

The PoCServe
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

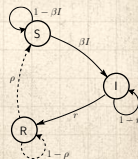
SIR is the virus

References

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 Three states:



Mathematical Epidemiology

The PoCserve
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

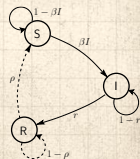
References

The standard **SIR model** [22]

 = basic model of disease contagion

 Three states:

1. S = Susceptible



Mathematical Epidemiology

The PoCverse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

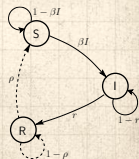
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 Three states:

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2. I = Infective/Infectious



Mathematical Epidemiology

The PoCVerse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

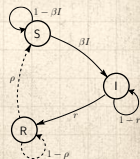
References

The standard **SIR model** [22]

 = basic model of disease contagion

 Three states:

1. S = Susceptible
2. I = Infective/Infectious
3. R = Recovered



Mathematical Epidemiology

The PoCVerse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

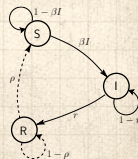
References

The standard **SIR model** [22]

 = basic model of disease contagion

 Three states:

1. S = Susceptible
2. I = Infective/Infectious
3. R = Recovered or Removed or Refractory



Mathematical Epidemiology

The PoCVerse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

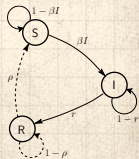
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🧱 = basic model of disease contagion

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1. S = Susceptible
2. I = Infective/Infectious
3. R = Recovered or Removed or Refractory

🧱 $S(t) + I(t) + R(t) = 1$



Mathematical Epidemiology

The PoCServe
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

The standard **SIR model** [22]

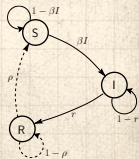
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🧱 Presumes random interactions (mass-action principle)



Mathematical Epidemiology

The PoCverse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

The standard **SIR model** [22]

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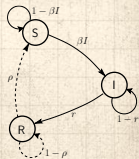
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🧱 Presumes random interactions (mass-action principle)

🧱 Interactions are independent (no memory)



Mathematical Epidemiology

The PoCverse
Biological Contagion
24 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

The standard **SIR model** [22]

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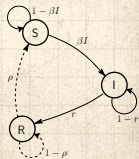
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2. **I** = Infective/Infectious
3. **R** = Recovered or Removed or Refractory

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

 Presumes random interactions (mass-action principle)

 Interactions are independent (no memory)

 Discrete and continuous time versions



Mathematical Epidemiology

The PoCServe
Biological Contagion
25 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

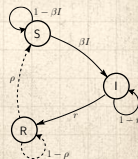
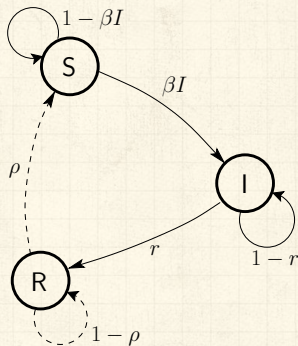
Nutshell

Other kinds of
prediction

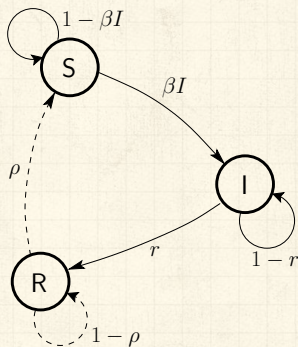
SIR is the virus

References

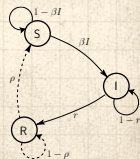
Discrete time automata example:



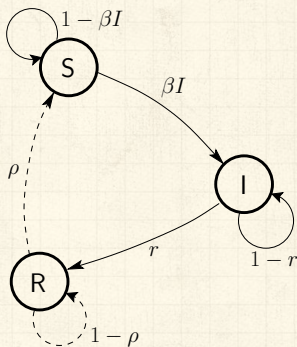
Discrete time automata example:



Transition Probabilities:

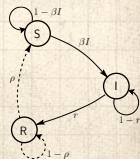


Discrete time automata example:

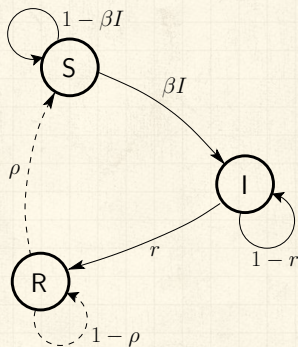


Transition Probabilities:

β for being infected given contact with infected

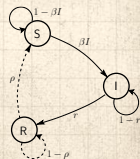


Discrete time automata example:

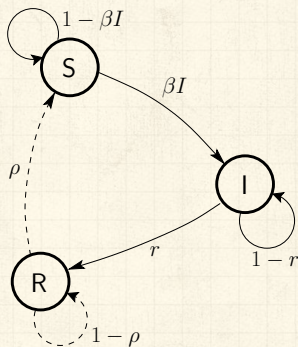


Transition Probabilities:

β for being infected given contact with infected
 r for recovery



Discrete time automata example:

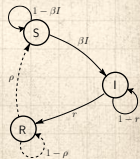


Transition Probabilities:

β for being infected given contact with infected

r for recovery

ρ for loss of immunity



Mathematical Epidemiology

Original models attributed to

The PoCServe
Biological Contagion
26 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

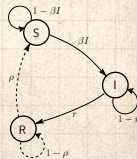
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Mathematical Epidemiology

Original models attributed to



1920's: Reed and Frost

The PoCServe
Biological Contagion
26 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

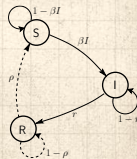
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Mathematical Epidemiology

The PoCServe
Biological Contagion
26 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

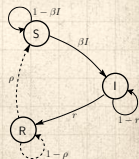
Original models attributed to



1920's: Reed and Frost



1920's/1930's: Kermack and McKendrick [17, 19, 18]



Mathematical Epidemiology

The PoCServe
Biological Contagion
26 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Original models attributed to



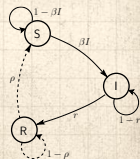
1920's: Reed and Frost



1920's/1930's: Kermack and McKendrick [17, 19, 18]



Coupled differential equations with a mass-action principle



Independent Interaction models

The PoCverse
Biological Contagion
27 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

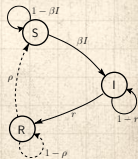
Differential equations for continuous model

$$\frac{d}{dt}S = -\beta IS + \rho R$$

$$\frac{d}{dt}I = \beta IS - rI$$

$$\frac{d}{dt}R = rI - \rho R$$

β , r , and ρ are now **rates**.



Reproduction Number R_0

The PoCServe
Biological Contagion
28 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

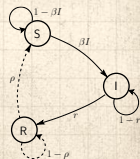
Nutshell

Other kinds of
prediction

SIR is the virus

References

Reproduction Number R_0 



Reproduction Number R_0

The PoCServe
Biological Contagion
28 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

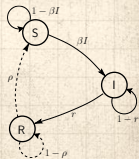
Other kinds of
prediction

SIR is the virus

References

Reproduction Number R_0 

 R_0 = expected number of infected individuals resulting from a single initial infective



Reproduction Number R_0

The PoCServe
Biological Contagion
28 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

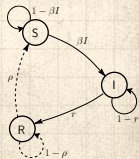
SIR is the virus

References

Reproduction Number R_0

 R_0 = expected number of infected individuals resulting from a single initial infective

 Epidemic threshold: If $R_0 > 1$, 'epidemic' occurs.



Reproduction Number R_0

The PoCverse
Biological Contagion
28 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

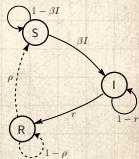
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Reproduction Number R_0

 R_0 = expected number of infected individuals resulting from a single initial infective

 Epidemic threshold: If $R_0 > 1$, 'epidemic' occurs.

 Exponential take off: R_0^n where n is the number of generations.



Reproduction Number R_0

The PoCverse
Biological Contagion
28 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

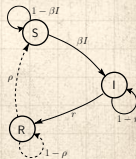
Other kinds of
prediction

SIR is the virus

References

Reproduction Number R_0

-  R_0 = expected number of infected individuals resulting from a single initial infective
-  Epidemic threshold: If $R_0 > 1$, 'epidemic' occurs.
-  Exponential take off: R_0^n where n is the number of generations.
-  Fantastically awful notation convention: R_0 and the R in *SIR*.



Reproduction Number R_0

Discrete version:



Set up: One Infective in a randomly mixing population of Susceptibles

The PoCVerse
Biological Contagion
29 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

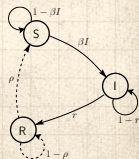
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

Discrete version:

- Set up: One Infective in a randomly mixing population of Susceptibles
- At time $t = 0$, single infective random bumps into a Susceptible

The PoCVerse
Biological Contagion
29 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

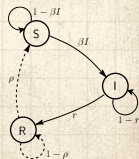
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

Discrete version:

- Set up: One Infective in a randomly mixing population of Susceptibles
- At time $t = 0$, single infective random bumps into a Susceptible
- Probability of transmission = β

The PoCVerse
Biological Contagion
29 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

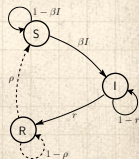
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

Discrete version:

- Set up: One Infective in a randomly mixing population of Susceptibles
- At time $t = 0$, single infective random bumps into a Susceptible
- Probability of transmission = β
- At time $t = 1$, single Infective remains infected with probability $1 - r$

The PoCVerse
Biological Contagion
29 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

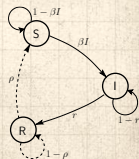
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

The PoCverse
Biological Contagion
29 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

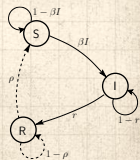
Other kinds of
prediction

SIR is the virus

References

Discrete version:

- Set up: One Infective in a randomly mixing population of Susceptibles
- At time $t = 0$, single infective random bumps into a Susceptible
- Probability of transmission = β
- At time $t = 1$, single Infective remains infected with probability $1 - r$
- At time $t = k$, single Infective remains infected with probability $(1 - r)^k$



Reproduction Number R_0

Discrete version:



Expected number infected by original infective:

$$R_0 = \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots$$

The PoCSverse
Biological Contagion
30 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

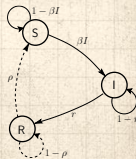
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

Discrete version:



Expected number infected by original infective:

$$R_0 = \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots$$

$$= \beta (1 + (1 - r) + (1 - r)^2 + (1 - r)^3 + \dots)$$

The PoCVerse
Biological Contagion
30 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

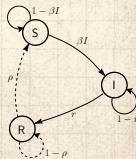
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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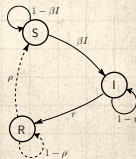


Expected number infected by original infective:

$$R_0 = \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots$$

$$= \beta (1 + (1 - r) + (1 - r)^2 + (1 - r)^3 + \dots)$$

$$= \beta \frac{1}{1 - (1 - r)}$$



Reproduction Number R_0

Discrete version:



Expected number infected by original infective:

$$R_0 = \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots$$

$$= \beta (1 + (1 - r) + (1 - r)^2 + (1 - r)^3 + \dots)$$

$$= \beta \frac{1}{1 - (1 - r)} = \beta / r$$

The PoCverse
Biological Contagion
30 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

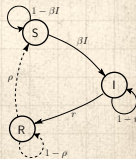
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Reproduction Number R_0

Discrete version:



Expected number infected by original infective:

$$R_0 = \beta + (1 - r)\beta + (1 - r)^2\beta + (1 - r)^3\beta + \dots$$

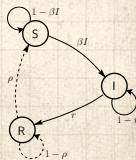
$$= \beta (1 + (1 - r) + (1 - r)^2 + (1 - r)^3 + \dots)$$

$$= \beta \frac{1}{1 - (1 - r)} = \beta / r$$

For $S(0) \simeq 1$ initial susceptibles

$(1 - S(0) = R(0) = \text{fraction initially immune})$:

$$R_0 = S(0)\beta / r$$



Independent Interaction models

The PoCServe
Biological Contagion
31 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

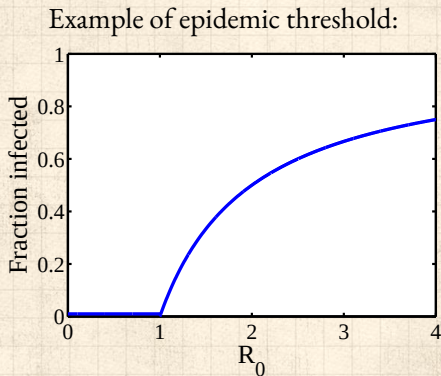
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

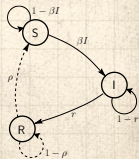
References



Continuous phase transition.



Fine idea from a simple model.



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

The PoCServe
Biological Contagion
32 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

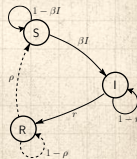
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

$$\frac{d}{dt}I = (\beta S - r)I$$

The PoCVerse
Biological Contagion
32 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

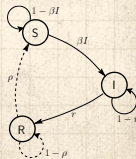
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

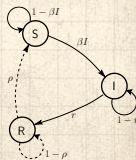
$$\frac{d}{dt}I = (\beta S - r)I$$



Number of infectives grows initially if

$$\beta S(0) - r > 0$$

where $S(0) \simeq 1$.



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

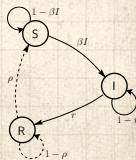
$$\frac{d}{dt}I = (\beta S - r)I$$



Number of infectives grows initially if

$$\beta S(0) - r > 0 \Rightarrow \beta S(0) > r$$

where $S(0) \simeq 1$.



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

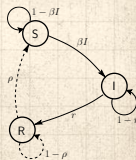
$$\frac{d}{dt}I = (\beta S - r)I$$



Number of infectives grows initially if

$$\beta S(0) - r > 0 \Rightarrow \beta S(0) > r \Rightarrow \beta S(0)/r > 1$$

where $S(0) \simeq 1$.



Independent Interaction models

For the continuous version



Second equation:

$$\frac{d}{dt}I = \beta SI - rI$$

$$\frac{d}{dt}I = (\beta S - r)I$$



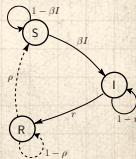
Number of infectives grows initially if

$$\beta S(0) - r > 0 \Rightarrow \beta S(0) > r \Rightarrow \beta S(0)/r > 1$$

where $S(0) \simeq 1$.



Same story as for discrete model.



Independent Interaction models

Many variants of the SIR model:

The PoCServe
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

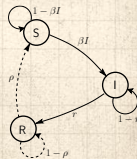
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Independent Interaction models

The PoCServe
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

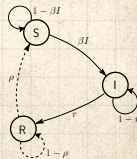
Other kinds of
prediction

SIR is the virus

References

Many variants of the SIR model:

 **SIS**: susceptible-infective-susceptible



Independent Interaction models

The PoCServe
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

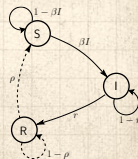
SIR is the virus

References

Many variants of the SIR model:

 **SIS**: susceptible-infective-susceptible

 **SIRS**: susceptible-infective-recovered-susceptible



Independent Interaction models

The PoCServe
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Many variants of the SIR model:



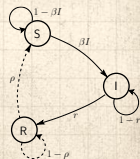
SIS: susceptible-infective-susceptible



SIRS: susceptible-infective-recovered-susceptible



compartment models (age or gender partitions)



Independent Interaction models

The PoCverse
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Many variants of the SIR model:



SIS: susceptible-infective-susceptible



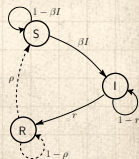
SIRS: susceptible-infective-recovered-susceptible



compartment models (age or gender partitions)



more categories such as 'exposed' (**SEIRS**)



Independent Interaction models

The PoCServe
Biological Contagion
33 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Many variants of the SIR model:



SIS: susceptible-infective-susceptible



SIRS: susceptible-infective-recovered-susceptible



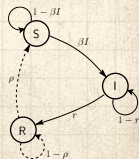
compartment models (age or gender partitions)



more categories such as 'exposed' (**SEIRS**)



recruitment (migration, birth)



Watch someone else pretend to save the world:



The PoCserve
Biological Contagion
34 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

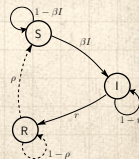
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Save the world yourself: 



 And you can be the virus. 

 Also contagious?: Cooperative games ...

The PoCVerse
Biological Contagion
35 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

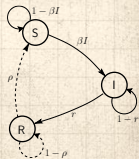
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Neural reboot—Save another pretend world with Vax:

The PoCServe
Biological Contagion
36 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

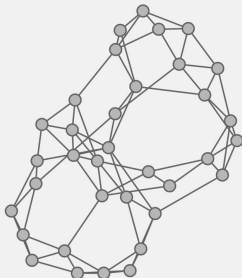
Nutshell

Other kinds of
prediction

SIR is the virus

References

Lesson 4: Quarantine



Vaccines take time to 'kick in' so they're ineffective if an infection has already begun to spread.

Start >

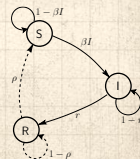
VAX!

Networks

Epidemics

Vaccines

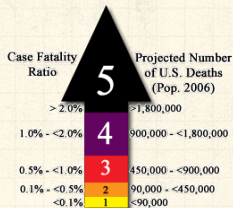
Quarantine



Pandemic severity index (PSI)



Classification during/post pandemic:



Assumes 30% illness rate
and unmitigated pandemic
without interventions

CDC

U.S. Gov.



Category based.



1–5 scale.



Modeled on the Saffir-Simpson
hurricane scale 



For novel diseases:

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

For novel diseases:

1. Can we predict the size of an epidemic?



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

For novel diseases:

1. Can we predict the size of an epidemic?
2. How important is the reproduction number R_0 ?



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R_0 approximately same for all of the following:



For novel diseases:

1. Can we predict the size of an epidemic?
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R_0 approximately same for all of the following:

-  1918-19 “Spanish Flu” ~ 75,000,000 world-wide, 500,000 deaths in US.



For novel diseases:

1. Can we predict the size of an epidemic?
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R_0 approximately same for all of the following:

-  1918-19 “Spanish Flu” $\sim$ 75,000,000 world-wide, 500,000 deaths in US.
-  1957-58 “Asian Flu” $\sim$ 2,000,000 world-wide, 70,000 deaths in US.



For novel diseases:

1. Can we predict the size of an epidemic?
2. How important is the reproduction number R_0 ?

R_0 approximately same for all of the following:

-  1918-19 “Spanish Flu” $\sim$ 75,000,000 world-wide, 500,000 deaths in US.
-  1957-58 “Asian Flu” $\sim$ 2,000,000 world-wide, 70,000 deaths in US.
-  1968-69 “Hong Kong Flu” $\sim$ 1,000,000 world-wide, 34,000 deaths in US.



For novel diseases:

1. Can we predict the size of an epidemic?
2. How important is the reproduction number R_0 ?

R_0 approximately same for all of the following:

-  1918-19 “Spanish Flu” $\sim$ 75,000,000 world-wide, 500,000 deaths in US.
-  1957-58 “Asian Flu” $\sim$ 2,000,000 world-wide, 70,000 deaths in US.
-  1968-69 “Hong Kong Flu” $\sim$ 1,000,000 world-wide, 34,000 deaths in US.
-  2003 “SARS Epidemic” $\sim$ 800 deaths world-wide.



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

The PoCVerse
Biological Contagion
39 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

 earthquakes (Gutenberg-Richter law)

The PoCVerse
Biological Contagion
39 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

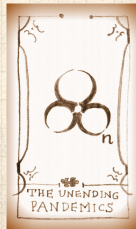
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

-  earthquakes (Gutenberg-Richter law)
-  city sizes, forest fires, war fatalities

The PoCVerse
Biological Contagion
39 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

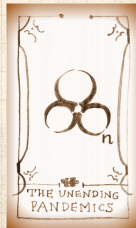
References



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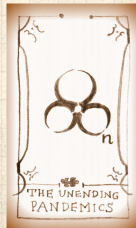
-  earthquakes (Gutenberg-Richter law)
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-  wealth distributions



Size distributions

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-  'popularity' (books, music, websites, ideas)



Size distributions

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-  **Epidemics?**

Power law distributions are common but not obligatory...



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

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Power law distributions are common but not obligatory...

Really, what about epidemics?



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

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-  city sizes, forest fires, war fatalities
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-  'popularity' (books, music, websites, ideas)
-  **Epidemics?**

Power law distributions are common but not obligatory...

Really, what about epidemics?

-  Simply hasn't attracted much attention.



Size distributions

As we know, heavy-tailed size distributions are somewhat prevalent in complex systems:

-  earthquakes (Gutenberg-Richter law)
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-  'popularity' (books, music, websites, ideas)
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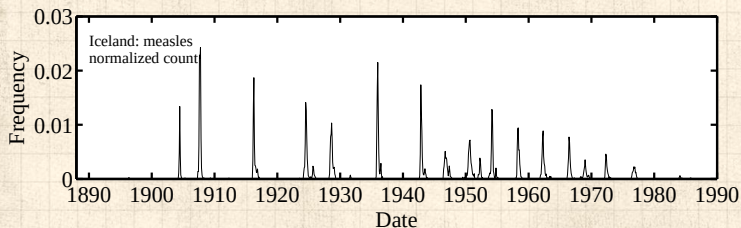
Power law distributions are common but not obligatory...

Really, what about epidemics?

-  Simply hasn't attracted much attention.
-  Data not as clean as for other phenomena.



Caseload recorded monthly for range of diseases in Iceland, 1888-1990



Treat outbreaks separated in time as ‘novel’ diseases.



Really not so good at all in Iceland

The PoCverse
Biological Contagion
41 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

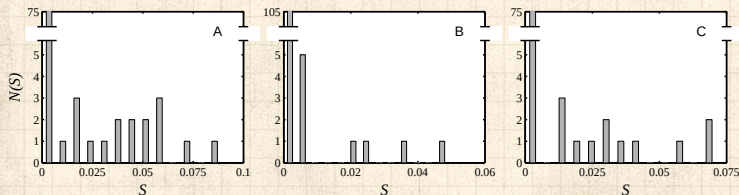
Nutshell

Other kinds of
prediction

SIR is the virus

References

Epidemic size distributions $N(S)$ for
Measles, Rubella, and Whooping Cough.



Spike near $S = 0$, relatively flat otherwise.



Measles & Pertussis

The PoCVerse
Biological Contagion
42 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

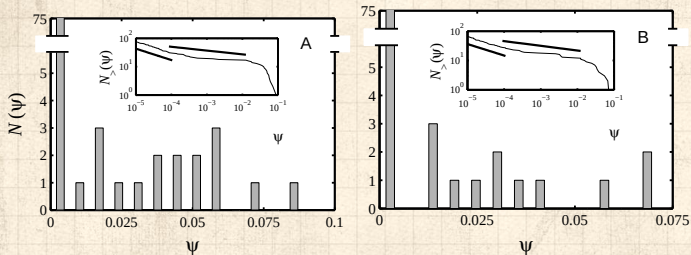
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Measles & Pertussis

The PoCServe
Biological Contagion
42 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

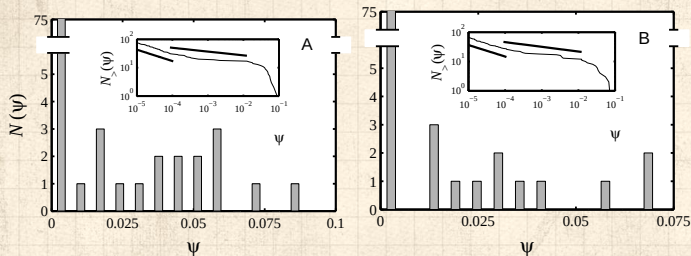
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

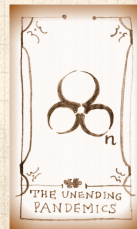


Insert plots:

Complementary cumulative frequency distributions:

$$N(\Psi' > \Psi) \propto \Psi^{-\gamma+1}$$

Limited scaling with a possible break.



Power law distributions

Measured values of γ :

The PoCVerse
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Power law distributions

The PoCSverse
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Measured values of γ :

 measles: 1.40 (low Ψ) and 1.13 (high Ψ)



Power law distributions

The PoCServe
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Measured values of γ :

-  measles: 1.40 (low Ψ) and 1.13 (high Ψ)
-  pertussis: 1.39 (low Ψ) and 1.16 (high Ψ)



Power law distributions

The PoCVerse
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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 Expect $2 \leq \gamma < 3$ (finite mean, infinite variance)



Power law distributions

The PoCVerse
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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 When $\gamma < 1$, can't normalize



Power law distributions

The PoCVerse
Biological Contagion
43 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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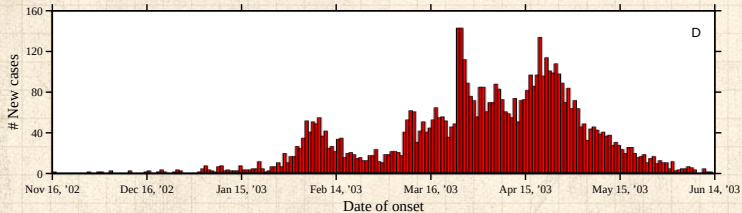
 Expect $2 \leq \gamma < 3$ (finite mean, infinite variance)

 When $\gamma < 1$, can't normalize

 Distribution is quite flat.



Resurgence—example of SARS



The PoCVerse
Biological Contagion
44 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

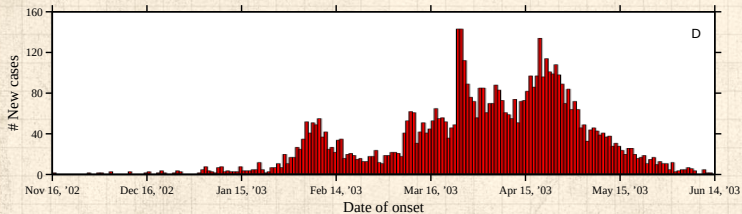
Other kinds of
prediction

SIR is the virus

References



Resurgence—example of SARS



Epidemic slows...

The PoCVerse
Biological Contagion
44 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

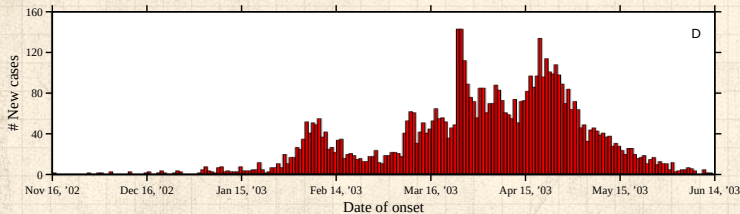
Other kinds of
prediction

SIR is the virus

References



Resurgence—example of SARS



Epidemic slows...
then an infective moves to a new context.

The PoCVerse
Biological Contagion
44 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

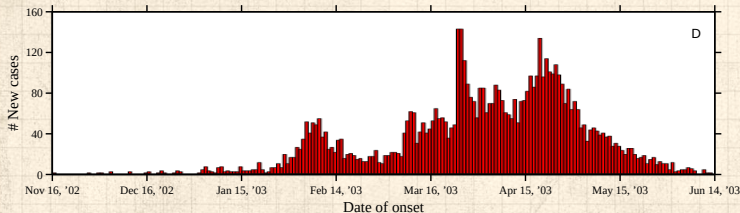
Other kinds of
prediction

SIR is the virus

References



Resurgence—example of SARS



Epidemic slows...
then an infective moves to a new context.



Epidemic discovers new 'pools' of susceptibles: **Resurgence.**

The PoCVerse
Biological Contagion
44 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

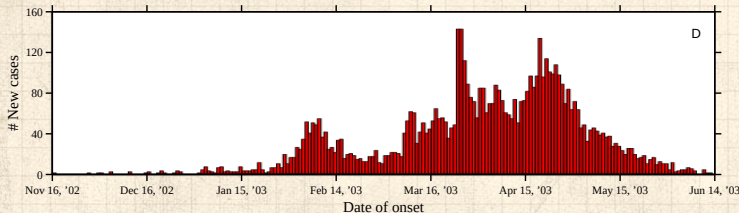
Other kinds of
prediction

SIR is the virus

References



Resurgence—example of SARS



Epidemic slows...
then an infective moves to a new context.



Epidemic discovers new 'pools' of susceptibles: **Resurgence.**



Importance of rare, stochastic events.

The PoCVerse
Biological Contagion
44 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

Community—S2E06: Epidemiology



Classified Phoenix.



The challenge

So... can a simple model produce

1. broad epidemic distributions
and
2. resurgence?

The PoCSverse
Biological Contagion
46 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

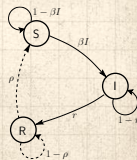
Model output

Nutshell

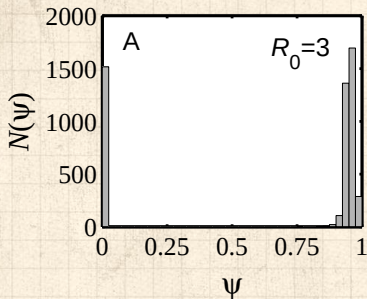
Other kinds of
prediction

SIR is the virus

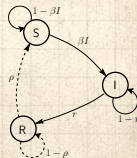
References



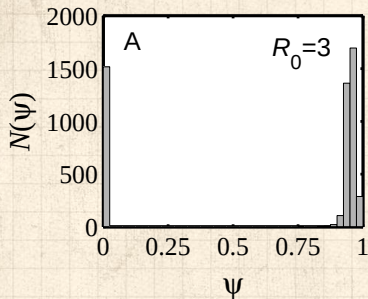
Size distributions



Simple models typically produce **bimodal** or **unimodal** size distributions.



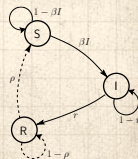
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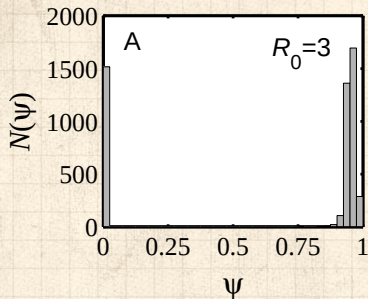
Simple models typically produce **bimodal** or **unimodal** size distributions.



This **includes** network models: random, small-world, scale-free, ...



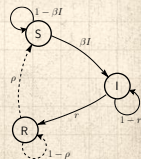
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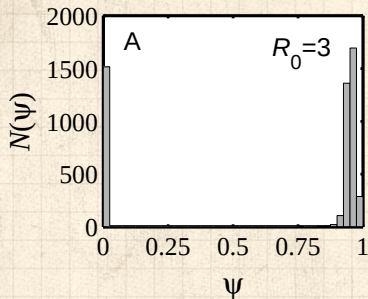
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🧱 This **includes** network models:
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🧱 Exceptions:



Size distributions

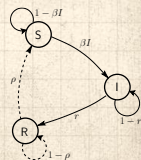


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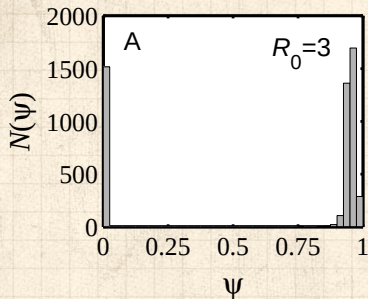
 This **includes** network models: random, small-world, scale-free, ...

 Exceptions:

1. Forest fire models



Size distributions



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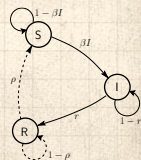


This **includes** network models: random, small-world, scale-free, ...



Exceptions:

1. Forest fire models
2. Sophisticated metapopulation models



Burning through the population

Forest fire models: [24]

The PoCVerse
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Burning through the population

Forest fire models: [24]



Rhodes & Anderson, 1996

The PoCServe
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



LIBERAL: WITH PRODS MAY BE ANNOYING SOMETIMES
BUT THERE'S NOTHING MORE DANGEROUS THAN
A PHYSICIST FIRST ENCOUNTERING A NEW SUBJECT

Burning through the population

Forest fire models: [24]

 Rhodes & Anderson, 1996

 The physicist's approach:
“if it works for magnets, it’ll work for people...”

The PoCServe
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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A bit of a stretch:

The PoCVerse
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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1. Epidemics $\equiv$ forest fires spreading on 3-d and 5-d lattices.

The PoCVerse
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Burning through the population

The PoCVerse
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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1. Epidemics $\equiv$ forest fires
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2. Claim Iceland and Faroe Islands exhibit power law
distributions for outbreaks.



Burning through the population

The PoCverse
Biological Contagion
48 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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A bit of a stretch:

1. Epidemics $\equiv$ forest fires spreading on 3-d and 5-d lattices.
2. Claim Iceland and Faroe Islands exhibit power law distributions for outbreaks.
3. Original forest fire model not completely understood.



Size distributions

The PoCVerse
Biological Contagion
49 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

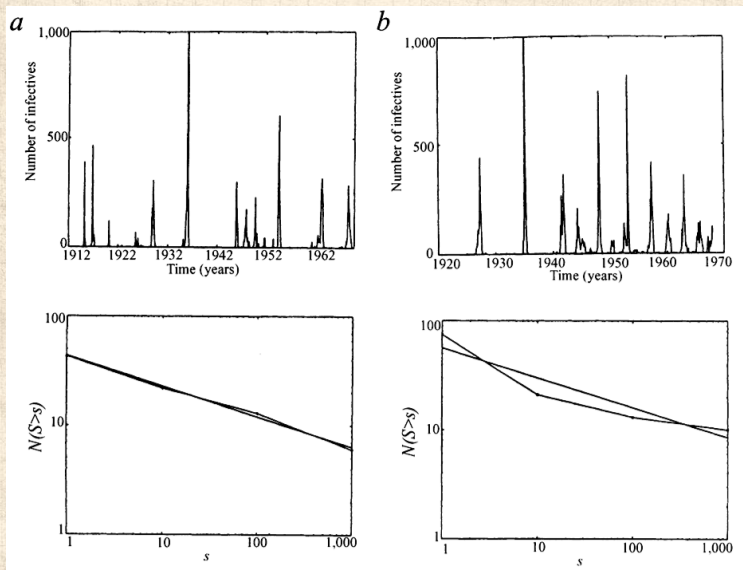
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

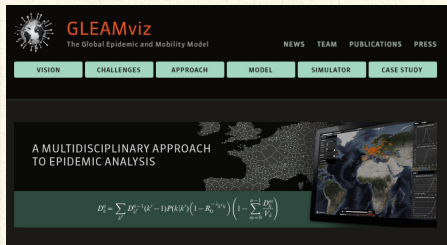


From Rhodes and Anderson, 1996.



Sophisticated metapopulation models:

- ✧ Multiscale models suggested earlier by others but not formalized (Bailey ^[1], Cliff and Haggett ^[9], Ferguson et al.)
- ✧ Community based mixing (two scales)—Longini. ^[21]
- ✧ Eubank et al.'s EpiSims/TRANSIMS —city simulations. ^[12]
- ✧ Spreading through countries—Airlines: Germann et al., Colizza et al. ^[10]



✧ GLEAM :
Global pandemic
simulations by
Vespignani et
al. ^[23]

The PoCServe
Biological Contagion
50 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

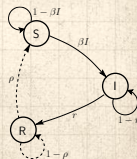
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

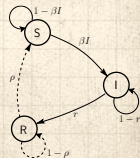
SIR is the virus

References



“The hidden geometry of complex, network-driven
contagion phenomena” 

Brockmann and Helbing,
Science, **342**, 1337–1342, 2013. ^[6]



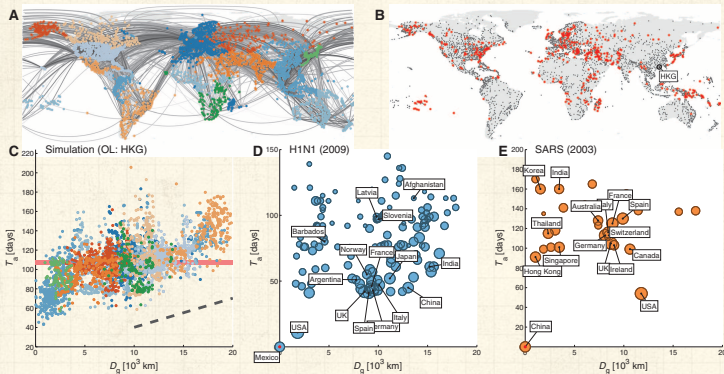
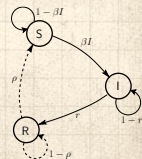


Fig. 1. Complexity in global, network-driven contagion phenomena. (A) The global mobility network (GMN). Gray lines represent passenger flows along direct connections between 4069 airports worldwide. Geographic regions are distinguished by color [classified according to network modularity maximization (39)]. (B) Temporal snapshot of a simulated global pandemic with initial outbreak location (OL) in Hong Kong (HKG). The simulation is based on the metapopulation model defined by Eq. 3 with parameters $R_0 = 1.5$, $\beta = 0.285 \text{ day}^{-1}$, $\gamma = 2.8 \times 10^{-3} \text{ day}^{-1}$, $\varepsilon = 10^{-6}$. Red symbols depict locations with epidemic arrival times in the time window $105 \text{ days} \leq T_a \leq 110 \text{ days}$. Because of the multiscale structure of the underlying network, the spatial distribution of disease prevalence (i.e., the fraction of infected individuals) lacks geometric coherence. No clear wave-front is visible, and based on this dynamic state, the OL cannot be easily deduced. (C) For the same simulation as in (B), the panel depicts arrival times T_a as a function of geographic distance D_g from the OL [nodes are colored according to geographic region as in (A)] for each of the 4069 nodes in the network. On a

global scale, T_a weakly correlates with geographic distance D_g ($R^2 = 0.34$). A linear fit yields an average global spreading speed of $v_g = 331 \text{ km/day}$ (see also fig. S7). Using D_g and v_g to estimate arrival times for specific locations, however, does not work well owing to the strong variability of the arrival times for a given geographic distance. The red horizontal bar corresponds to the arrival time window shown in (B). (D) Arrival times versus geographic distance from the source (Mexico) for the 2009 H1N1 pandemic. Symbols represent 140 affected countries, and symbol size quantifies total traffic per country. Arrival times are defined as the date of the first confirmed case in a given country after the initial outbreak on 17 March 2009. As in the simulated scenario, arrival time and geographic distance are only weakly correlated ($R^2 = 0.0394$). (E) In analogy to (D), the panel depicts the arrival times versus geographic distance from the source (China) of the 2003 SARS epidemic for 29 affected countries worldwide. Arrival times are taken from WHO published data (2). As in (C) and (D), arrival time correlates weakly with geographic distance.



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

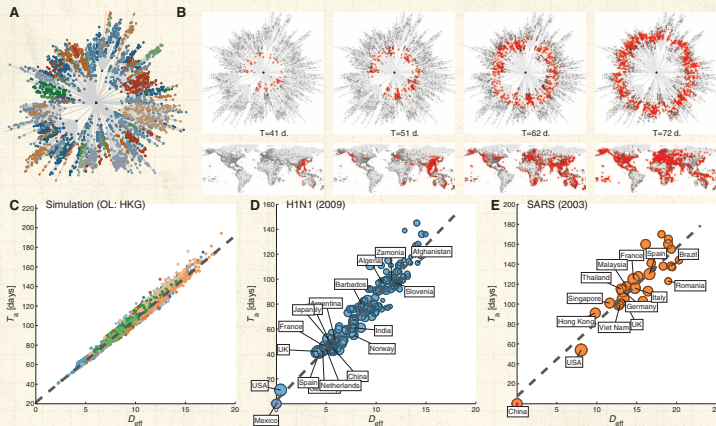
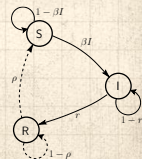


Fig. 2. Understanding global contagion phenomena using effective distance. (A) The structure of the shortest path tree (in gray) from Hong Kong (central node). Radial distance represents effective distance D_{eff} as defined by Eqs. 4 and 5. Nodes are colored according to the same scheme as in Fig. 1A. (B) The sequence (from left to right) of panels depicts the time course of a simulated model with initial outbreak in Hong Kong (HKG), for the same parameter set as used in Fig. 1B. Prevalence is reflected by the redness of the symbols. Each panel compares the state of the system in the conventional geographic representation (bottom) with the effective distance representation (top). The complex spatial pattern in the conventional view is equivalent to a homoge-

neous wave that propagates outwards at constant effective speed in the effective distance representation. (C) Epidemic arrival time T_a versus effective distance D_{eff} for the same simulated epidemic as in (B). In contrast to geographic distance (Fig. 1C), effective distance correlates strongly with arrival time ($R^2 = 0.973$), i.e., effective distance is an excellent predictor of arrival times. (D and E) Linear relationship between effective distance and arrival time for the 2009 H1N1 pandemic (D) and the 2003 SARS epidemic (E). The arrival time data are the same as in Fig. 1, D and E. The effective distance was computed from the projected global mobility network between countries. As in the model system, we observe a strong correlation between arrival time and effective distance.



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

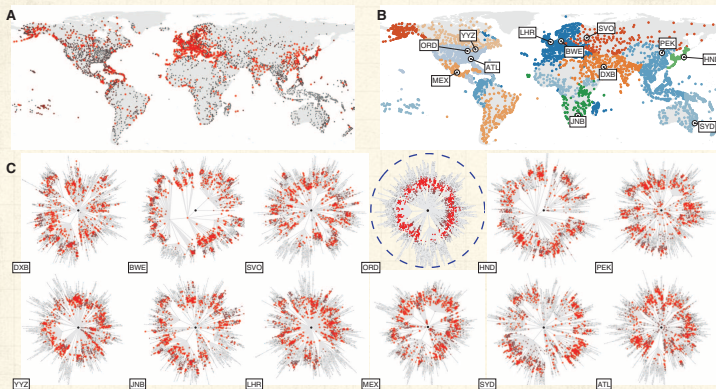
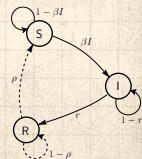


Fig. 3. Qualitative outbreak reconstruction based on effective distance. (A) Spatial distribution of prevalence $j_n(t)$ at time $T = 81$ days for OL Chicago (parameters $\beta = 0.28 \text{ day}^{-1}$, $R_0 = 1.9$, $\gamma = 2.8 \times 10^{-3} \text{ day}^{-1}$, and $\varepsilon = 10^{-4}$). After this time, it is difficult, if not impossible, to determine the correct OL from snapshots of the dynamics. (B) Candidate OLs chosen from different geographic regions. (C) Panels depict the state of the system shown in (A) from the

perspective of each candidate OL, using each OL's shortest path tree representation. Only the actual OL (ORD, circled in blue) produces a circular wavefront. Even for comparable North American airports [Atlanta (ATL), Toronto (YYZ), and Mexico City (MEX)], the wavefronts are not nearly as concentric. Effective distances thus permit the extraction of the correct OL, based on information on the mobility network and a single snapshot of the dynamics.



Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

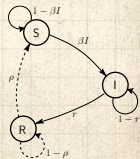
SIR is the virus

References

Community—S2E06: Epidemiology



Scenario B.



Size distributions

The PoCServe
Biological Contagion
56 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

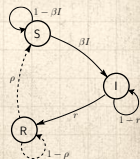
Other kinds of
prediction

SIR is the virus

References



Vital work but perhaps hard to generalize from...



Size distributions



Vital work but perhaps hard to generalize from...



⇒ Create a simple model involving multiscale travel

The PoCServe
Biological Contagion
56 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

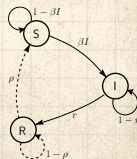
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Size distributions



Vital work but perhaps hard to generalize from...



⇒ Create a simple model involving multiscale travel



Very big question: **What is N ?**

The PoCServe
Biological Contagion
56 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

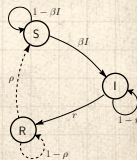
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Size distributions

The PoCServe
Biological Contagion
56 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Vital work but perhaps hard to generalize from...



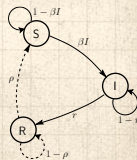
⇒ Create a simple model involving multiscale travel



Very big question: **What is N ?**

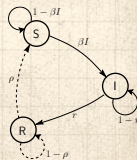


Should we model SARS in Hong Kong as spreading in a neighborhood, in Hong Kong, Asia, or the world?



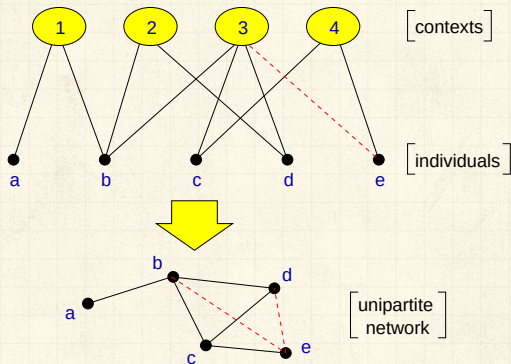
Size distributions

- ✉ Vital work but perhaps hard to generalize from...
- ✉ $\Rightarrow$ Create a simple model involving multiscale travel
- ✉ Very big question: **What is N ?**
- ✉ Should we model SARS in Hong Kong as spreading in a neighborhood, in Hong Kong, Asia, or the world?
- ✉ For simple models, we need to know the final size beforehand...



Improving simple models

Contexts and Identities—Bipartite networks



The PoCServe
Biological Contagion
57 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

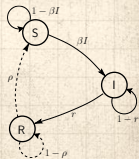
Model output

Nutshell

Other kinds of
prediction

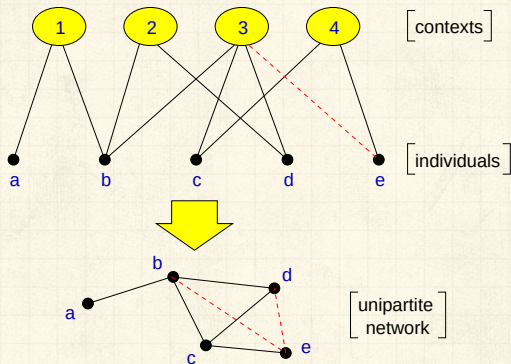
SIR is the virus

References



Improving simple models

Contexts and Identities—Bipartite networks



boards of directors

The PoCverse
Biological Contagion
57 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

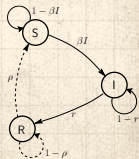
Model output

Nutshell

Other kinds of
prediction

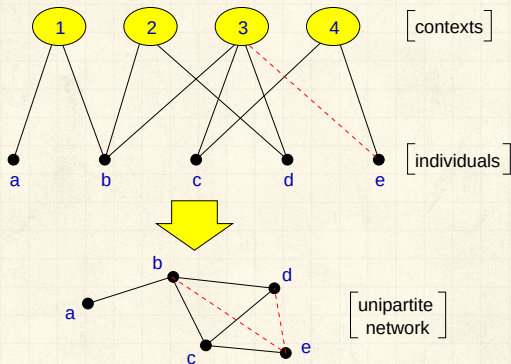
SIR is the virus

References



Improving simple models

Contexts and Identities—Bipartite networks



boards of directors



movies

The PoCverse
Biological Contagion
57 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

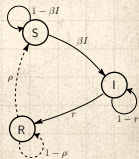
Model output

Nutshell

Other kinds of
prediction

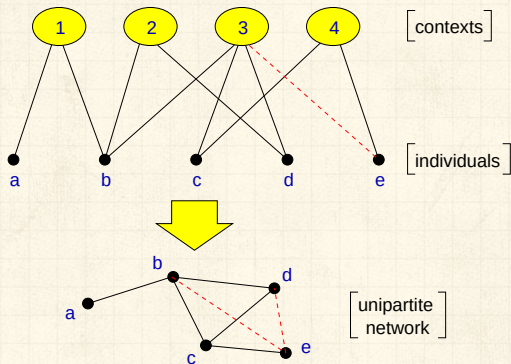
SIR is the virus

References



Improving simple models

Contexts and Identities—Bipartite networks



boards of directors



movies



transportation modes (subway)

The PoCVerse
Biological Contagion
57 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

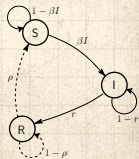
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

The PoCServe
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

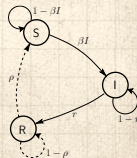
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:

The PoCSverse
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

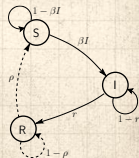
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:



Geographic location

The PoCServe
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

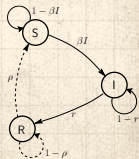
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:



Geographic location



Type of employment

The PoCSverse
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

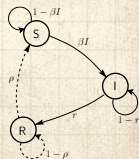
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:



Geographic location



Type of employment



Age

The PoCVerse
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

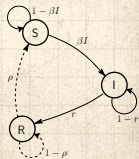
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:

-  Geographic location
-  Type of employment
-  Age
-  Recreational activities

The PoCServe
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

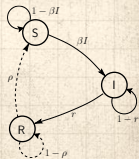
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



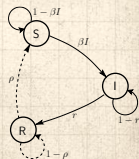
Improving simple models

Idea for social networks: incorporate identity

Identity is formed from attributes such as:

-  Geographic location
-  Type of employment
-  Age
-  Recreational activities

Groups are crucial...



Improving simple models

The PoCVerse
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

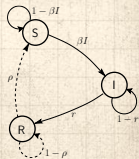
Idea for social networks: incorporate identity

Identity is formed from attributes such as:

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-  Age
-  Recreational activities

Groups are crucial...

-  formed by people with at least one similar attribute



Improving simple models

The PoCverse
Biological Contagion
58 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

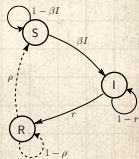
Idea for social networks: incorporate identity

Identity is formed from attributes such as:

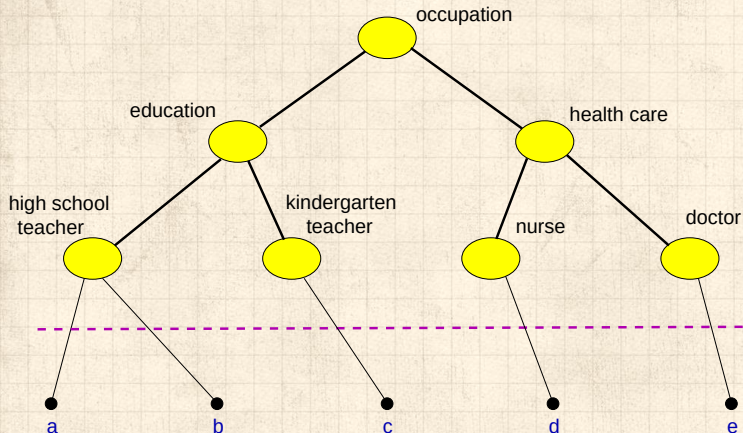
-  Geographic location
-  Type of employment
-  Age
-  Recreational activities

Groups are crucial...

-  formed by people with at least one similar attribute
-  Attributes $\Leftrightarrow$ Contexts $\Leftrightarrow$ Interactions $\Leftrightarrow$ Networks. [27]



Infer interactions/network from identities



Distance makes sense in identity/context space.

The PoCServe
Biological Contagion
59 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

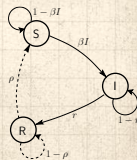
Model output

Nutshell

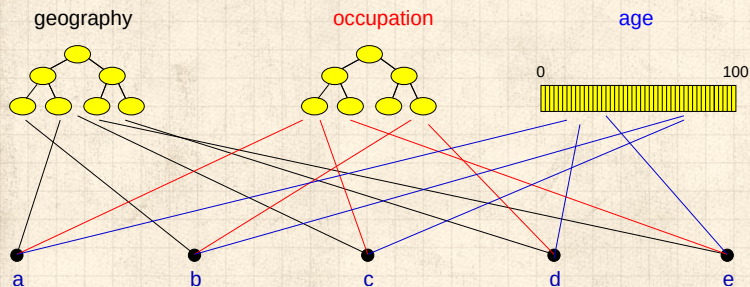
Other kinds of
prediction

SIR is the virus

References



Generalized context space



(Blau & Schwartz ^[4], Simmel ^[25], Breiger ^[5])

The PoCServe
Biological Contagion
60 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

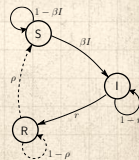
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” ↗

Watts et al.,

Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. [28]

Geography: allow people to move between contexts

The PoCSverse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

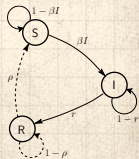
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



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Geography: allow people to move between contexts



Locally: standard SIR model with random mixing

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

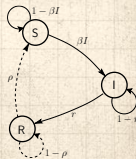
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” ↗

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Geography: allow people to move between contexts



Locally: standard SIR model with random mixing



discrete time simulation

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

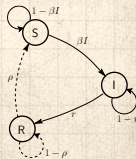
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” 

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Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. ^[28]

Geography: allow people to move between contexts



Locally: standard SIR model with random mixing



discrete time simulation



β = infection probability

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

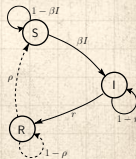
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” ↗

Watts et al.,

Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. [28]

Geography: allow people to move between contexts



Locally: standard SIR model with random mixing



discrete time simulation



β = infection probability



γ = recovery probability

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

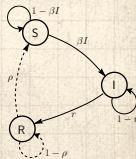
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” 

Watts et al.,

Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. [28]

Geography: allow people to move between contexts



Locally: standard SIR model with random mixing



discrete time simulation



β = infection probability



γ = recovery probability



P = probability of travel

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

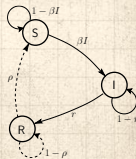
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” ↗

Watts et al.,

Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. [28]

Geography: allow people to move between contexts



Locally: standard SIR model with random mixing



discrete time simulation



β = infection probability



γ = recovery probability



P = probability of travel



Movement distance: $\Pr(d) \propto \exp(-d/\xi)$

The PoCVerse
Biological Contagion
61 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

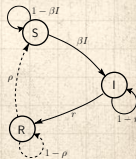
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



A toy agent-based model:



“Multiscale, resurgent epidemics in a hierarchical metapopulation model” ↗

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Proc. Natl. Acad. Sci., **102**, 11157–11162, 2005. [28]

Geography: allow people to move between contexts

Locally: standard SIR model with random mixing

discrete time simulation

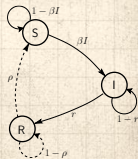
β = infection probability

γ = recovery probability

P = probability of travel

Movement distance: $\Pr(d) \propto \exp(-d/\xi)$

ξ = typical travel distance



A toy agent-based model

The PoCServe
Biological Contagion
62 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

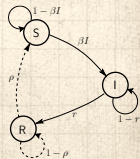
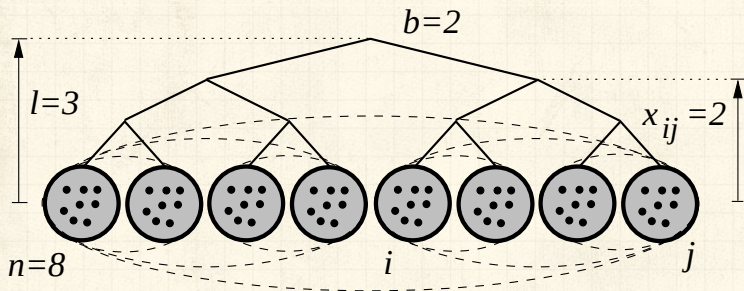
Nutshell

Other kinds of
prediction

SIR is the virus

References

Schematic:



Model output



Define P_0 = Expected number of infected individuals **leaving** initially infected context.

The PoCSverse
Biological Contagion
63 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

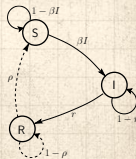
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Model output

- Define P_0 = Expected number of infected individuals **leaving** initially infected context.
- Need $P_0 > 1$ for disease to spread (independent of R_0).

The PoCSverse
Biological Contagion
63 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

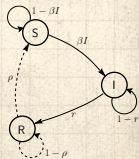
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Model output

- Define P_0 = Expected number of infected individuals **leaving** initially infected context.
- Need $P_0 > 1$ for disease to spread (independent of R_0).
- Limit epidemic size by **restricting frequency of travel and/or range**

The PoCSverse
Biological Contagion
63 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

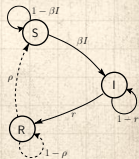
Model output

Nutshell

Other kinds of
prediction

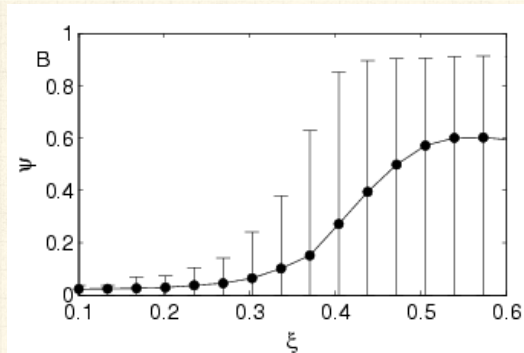
SIR is the virus

References



Model output

Varying ξ :



Transition in expected final size based on typical movement distance

The PoCverse
Biological Contagion
64 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

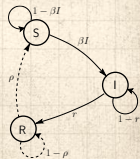
Model output

Nutshell

Other kinds of
prediction

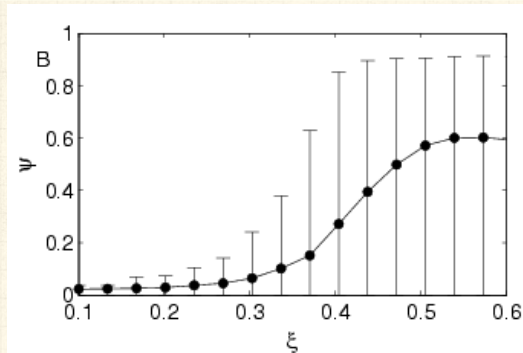
SIR is the virus

References



Model output

Varying ξ :



Transition in expected final size based on typical movement distance (**sensible**)

The PoCServe
Biological Contagion
64 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

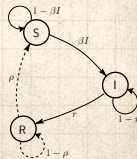
Model output

Nutshell

Other kinds of
prediction

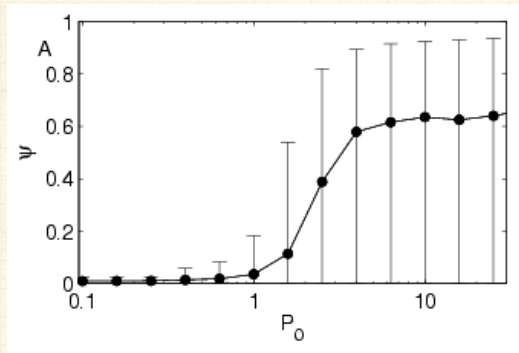
SIR is the virus

References



Model output

Varying P_0 :



Transition in expected final size based on typical number of infectives leaving first group

The PoCserve
Biological Contagion
65 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

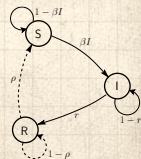
Model output

Nutshell

Other kinds of
prediction

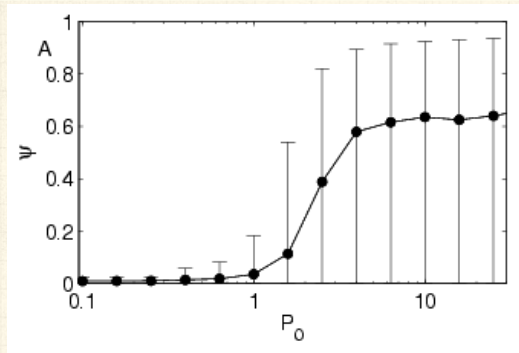
SIR is the virus

References



Model output

Varying P_0 :



Transition in expected final size based on typical number of infectives leaving first group (also sensible)

The PoCverse
Biological Contagion
65 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

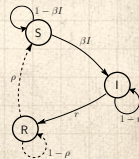
Model output

Nutshell

Other kinds of
prediction

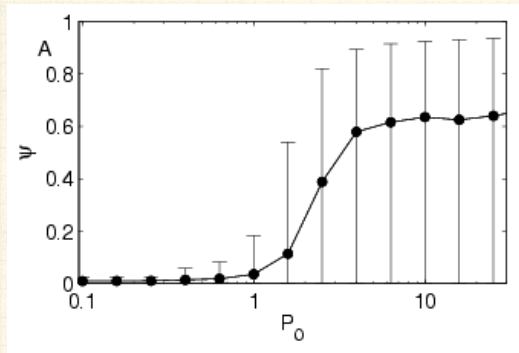
SIR is the virus

References



Model output

Varying P_0 :



Transition in expected final size based on typical number of infectives leaving first group (also sensible)



Travel advisories: ξ has larger effect than P_0 .

The PoCverse
Biological Contagion
65 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

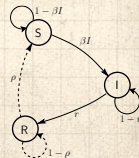
Model output

Nutshell

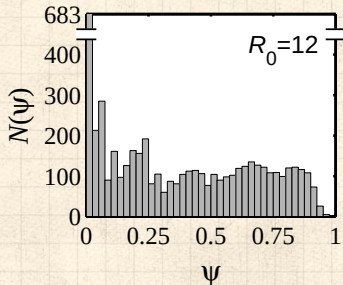
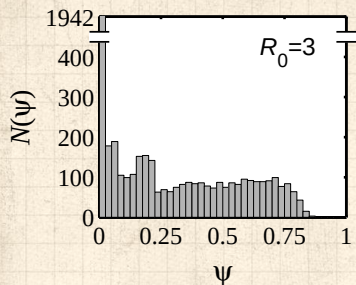
Other kinds of
prediction

SIR is the virus

References



Example model output: size distributions



The PoCServe
Biological Contagion
66 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

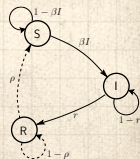
Model output

Nutshell

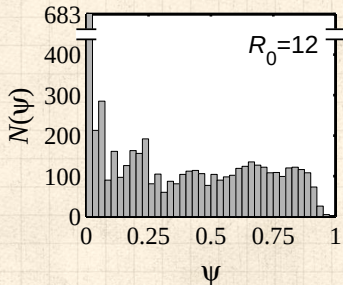
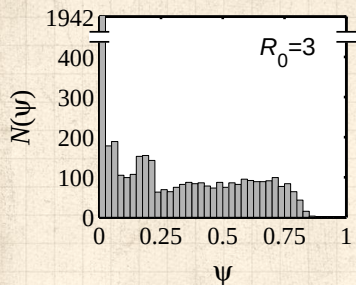
Other kinds of
prediction

SIR is the virus

References



Example model output: size distributions



The PoCServe
Biological Contagion
66 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

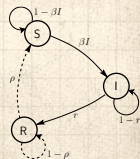
Model output

Nutshell

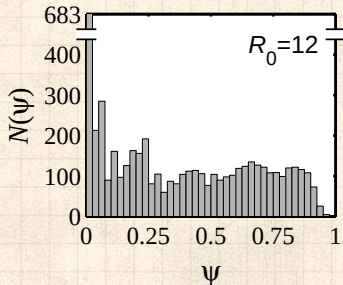
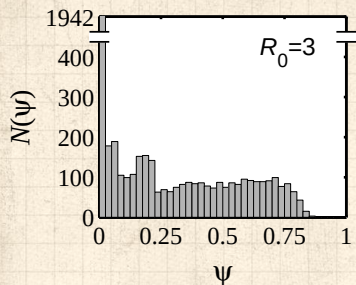
Other kinds of
prediction

SIR is the virus

References



Example model output: size distributions



Flat distributions are possible for certain ξ and P .

The PoCServe
Biological Contagion
66 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

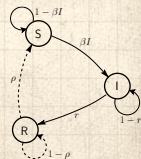
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Example model output: size distributions

The PoCServe
Biological Contagion
66 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

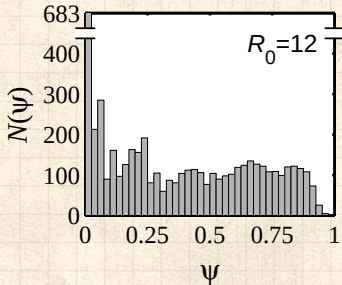
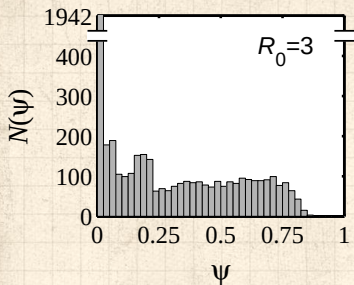
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

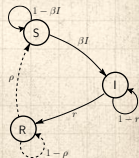
References



Flat distributions are possible for certain ξ and P .



Different R_0 's may produce similar distributions



Example model output: size distributions

The PoCVerse
Biological Contagion
66 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

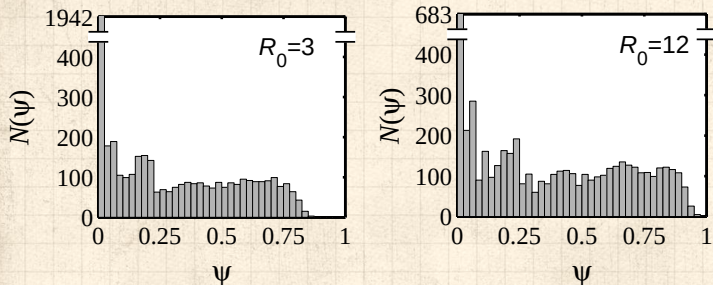
Model output

Nutshell

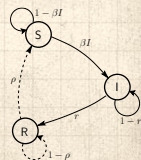
Other kinds of
prediction

SIR is the virus

References



- Flat distributions are possible for certain ξ and P .
- Different R_0 's may produce similar distributions
- Same epidemic sizes may arise from different R_0 's



Model output—resurgence

The PoCSverse
Biological Contagion
67 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

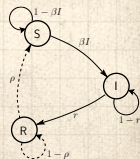
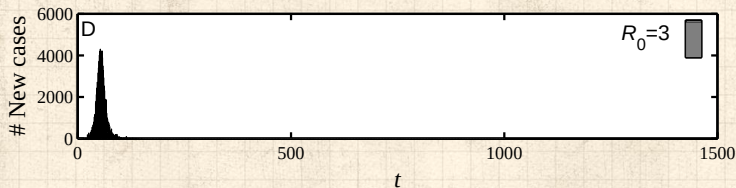
Nutshell

Other kinds of
prediction

SIR is the virus

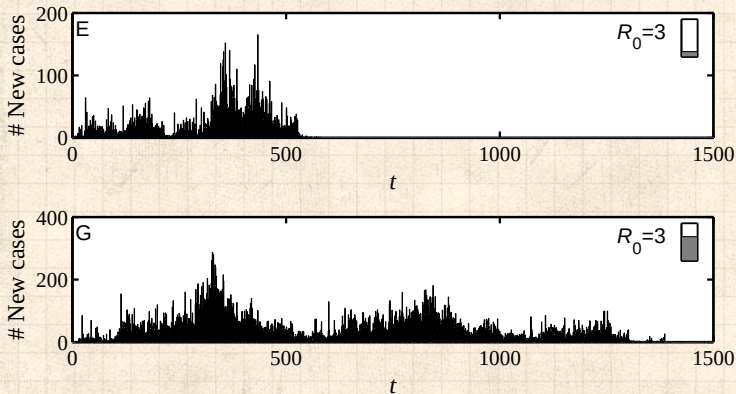
References

Standard model:



Model output—resurgence

Standard model with transport:



The PoCServe
Biological Contagion
68 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

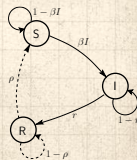
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The upshot

Simple multiscale population structure

The PoCSverse
Biological Contagion
69 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

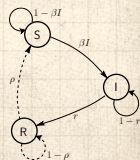
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The upshot

Simple multiscale population structure
+
stochasticity

The PoCSverse
Biological Contagion
69 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

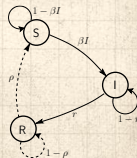
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The upshot

Simple multiscale population structure

+

stochasticity

leads to

resurgence

+

broad epidemic size distributions

The PoCSverse
Biological Contagion
69 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

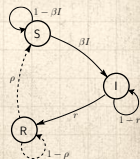
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The Last of Us: Groups

The PoCVerse
Biological Contagion
70 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

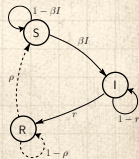
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



The Last of Us: Groups

The PoCVerse
Biological Contagion
72 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

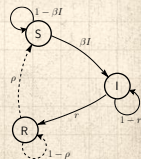
Model output

Nutshell

Other kinds of
prediction

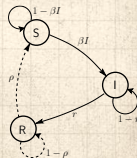
SIR is the virus

References





For the hierarchical movement model, epidemic size is highly unpredictable



Nutshelling



For the hierarchical movement model, epidemic size is highly unpredictable



Model is more complicated than SIR but still simple.

The PoCSverse
Biological Contagion
74 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

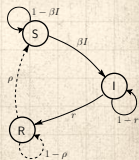
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Nutshelling

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.

The PoCSverse
Biological Contagion
74 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

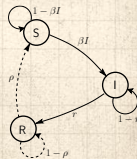
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Nutshelling

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is not terribly useful.

The PoCSverse
Biological Contagion
74 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

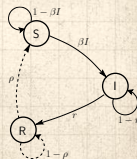
Model output

Nutshell

Other kinds of
prediction

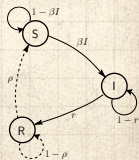
SIR is the virus

References



Nutshelling

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is not terribly useful.
- R_0 , however measured, is not informative about



Nutshelling

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is not terribly useful.
- R_0 , however measured, is not informative about
 - how likely the observed epidemic size was,

The PoCSverse
Biological Contagion
74 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

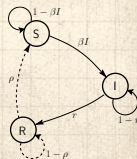
Model output

Nutshell

Other kinds of
prediction

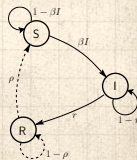
SIR is the virus

References



Nutshelling

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is not terribly useful.
- R_0 , however measured, is not informative about
 - how likely the observed epidemic size was,
 - and how likely future epidemics will be.



Nutshelling

The PoCServe
Biological Contagion
74 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

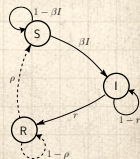
Nutshell

Other kinds of
prediction

SIR is the virus

References

- For the hierarchical movement model, epidemic size is highly unpredictable
- Model is more complicated than SIR but still simple.
- We haven't even included normal social responses such as travel bans and self-quarantine.
- The reproduction number R_0 is not terribly useful.
- R_0 , however measured, is not informative about
 1. how likely the observed epidemic size was,
 2. and how likely future epidemics will be.
- Problem: R_0 summarises **one** epidemic after the fact and enfold movement, the price of bananas, everything.



Conclusions



Disease's spread is highly sensitive to population structure.

The PoCSverse
Biological Contagion
75 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

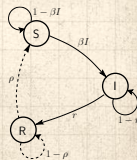
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Conclusions

- ❏ Disease's spread is highly sensitive to population structure.
- ❏ Rare events may matter enormously:

The PoCSverse
Biological Contagion
75 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

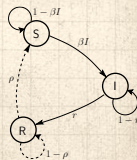
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Conclusions

- ❏ Disease's spread is highly sensitive to population structure.
- ❏ Rare events may matter enormously: e.g., an infected individual taking an international flight.

The PoCVerse
Biological Contagion
75 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

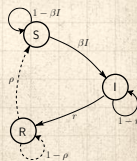
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Conclusions

- 🧱 Disease's spread is highly sensitive to population structure.
- 🧱 Rare events may matter enormously: e.g., an infected individual taking an international flight.
- 🧱 More support for controlling population movement:

The PoCSverse
Biological Contagion
75 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

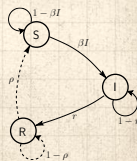
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Conclusions

- ❏ Disease's spread is highly sensitive to population structure.
- ❏ Rare events may matter enormously: e.g., an infected individual taking an international flight.
- ❏ More support for controlling population movement: e.g., travel advisories, quarantine

The PoCVerse
Biological Contagion
75 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

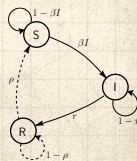
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Nutshelling

What to do:

The PoCSverse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

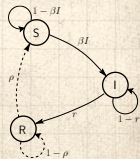
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Nutshelling

What to do:

 Need to separate movement from disease

The PoCSverse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

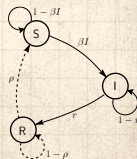
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCSverse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

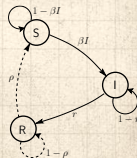
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Nutshelling

The PoCSverse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

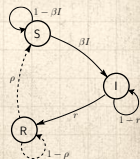
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prediction

SIR is the virus

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What to do:

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Nutshelling

The PoCVerse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

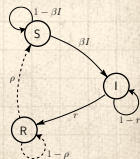
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Nutshelling

The PoCverse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

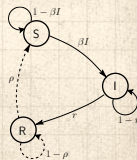
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More wondering:



Nutshelling

The PoCVerse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

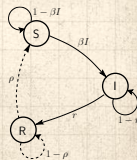
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- Exactly how important are rare events in disease spreading?



Nutshelling

The PoCVerse
Biological Contagion
76 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

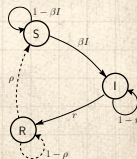
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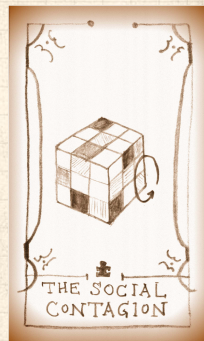
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More wondering:

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- Again, what is N ?





Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

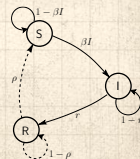
Nutshell

Other kinds of
prediction

SIR is the virus

References

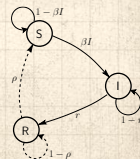
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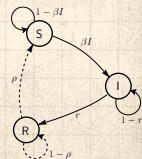
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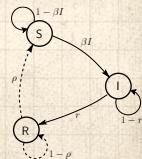
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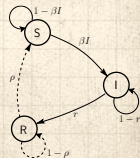
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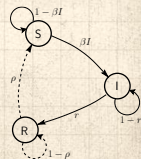
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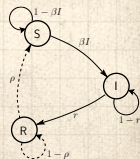
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¹<http://www.redherring.com/mag/issue55/economics.html>

Economics, Schmeconomics

Alan Greenspan (September 18, 2007):



<http://wikipedia.org>

The PoCVerse
Biological Contagion
79 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

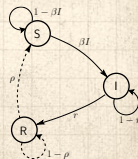
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCSverse
Biological Contagion
79 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

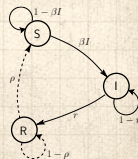
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Economics, Schmeconomics

The PoCVerse
Biological Contagion
79 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

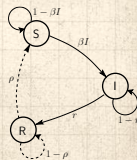
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The PoCVerse
Biological Contagion
79 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

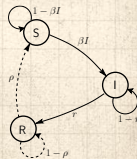
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Economics, Schmeconomics

The PoCSverse
Biological Contagion
79 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References

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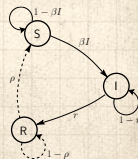
If I could figure out a way to determine whether or not people are more fearful or changing to more euphoric,

I don’t need any of this other stuff.

I could forecast the economy better than any way I know.”



<http://wikipedia.org>



Economics, Schmeconomics

Greenspan continues:

The PoCSverse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

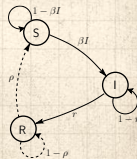
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

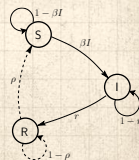
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

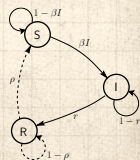
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

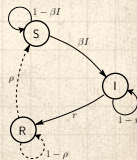
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

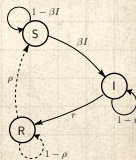
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCServe
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

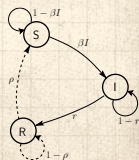
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCverse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

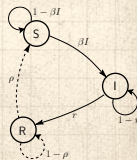
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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Jon Stewart:

“You just bummed the @*!# out of me.”



wildbluffmedia.com



From the Daily Show  (September 18, 2007)



The full episode is here:

<http://www.cc.com/video-clips/cenrt5/the-daily-show-with-jon-stewart-alan-g>

The PoCVerse
Biological Contagion
80 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

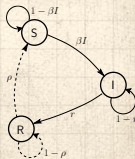
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Predicting social catastrophe isn't easy...

“Greenspan Concedes Error on Regulation”

New York Times, October 23, 2008 

The PoCServe
Biological Contagion
81 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

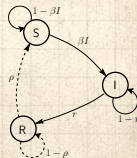
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCServe
Biological Contagion
81 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

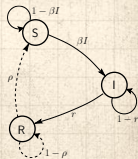
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
81 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

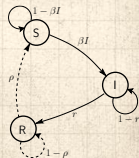
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
81 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

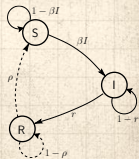
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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- Rep. Henry A. Waxman: "Do you feel that your ideology pushed you to make decisions that you wish you had not made?"
- Mr. Greenspan conceded: "Yes, I've found a flaw. I don't know how significant or permanent it is. But I've been very distressed by that fact."

New York Times, October 23, 2008 

The PoCServe
Biological Contagion
81 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

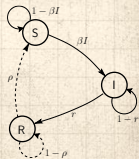
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



Economics, Schmeconomics

James K. Galbraith:

From the New York Times, 11/02/2008 

The PoCVerse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

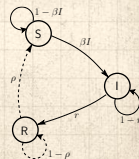
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

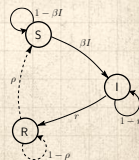
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCverse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

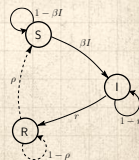
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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NYT What does that say about the field of economics, which claims to be a science?

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The PoCVerse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

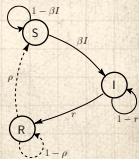
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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From the New York Times, 11/02/2008 

The PoCVerse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

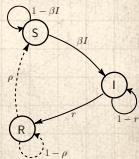
Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



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The PoCVerse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

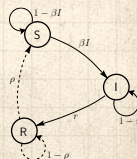
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Nutshell

Other kinds of
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The PoCSverse
Biological Contagion
82 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

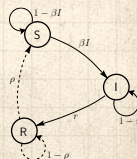
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References



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The PoCServe
Biological Contagion
83 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

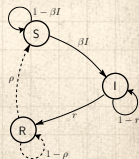
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Nutshell

Other kinds of
prediction

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References



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The PoCServe
Biological Contagion
83 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

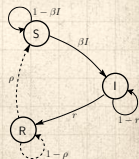
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Nutshell

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The PoCServe
Biological Contagion
83 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

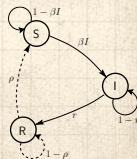
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Nutshell

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The PoCServe
Biological Contagion
83 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

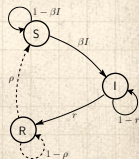
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Nutshell

Other kinds of
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SIR is the virus

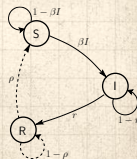
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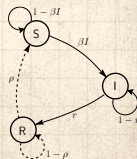
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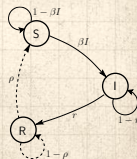


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Social contagion:



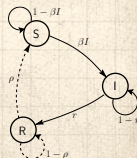
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Social contagion:

- SIR may apply sometimes ...



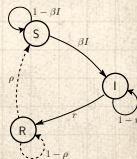
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Social contagion:

- SIR may apply sometimes ...
- But we need new fundamental models.



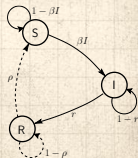
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- Next up: Thresholds.



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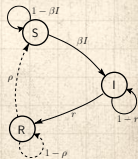
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Social contagion:

- SIR may apply sometimes ...
- But we need new fundamental models.
- Next up: Thresholds.

¹Apologies sir, I’m afraid our chefs can’t help themselves!



We really should know social contagion is different but ...

The PoCServe
Biological Contagion
84 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

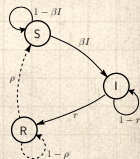
References



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“It’s contagious: Rethinking a metaphor
dialogically” 

Warren and Power,
Culture & Psychology, **21**, 359–379, 2015. [26]



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The PoCServe
Biological Contagion
84 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

Model output

Nutshell

Other kinds of
prediction

SIR is the virus

References



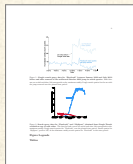
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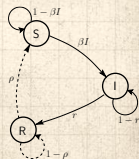


“Facebook will lose 80% of users by 2017, say Princeton researchers” ↗ (Guardian, 2014)

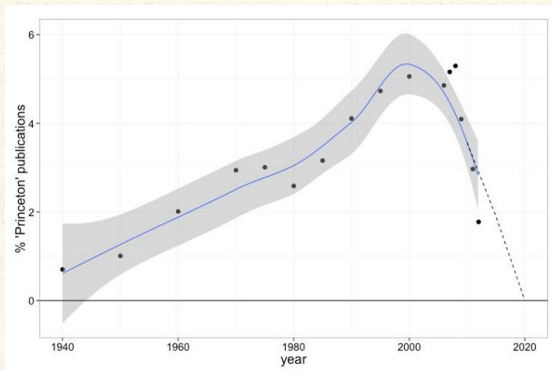


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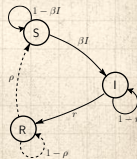
The Facebook Data Science team's response [?]:



Mike Develin, Lada Adamic, and Sean Taylor.

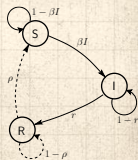


See also: The pending demise of Facebook (and Princeton)  (filed under Awesomeness) ^[20]



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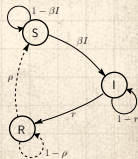
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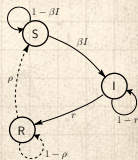
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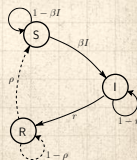
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The PoCverse
Biological Contagion
90 of 93

Introduction

Simple disease
spreading models

Prediction

More models

Toy metapopulation
models

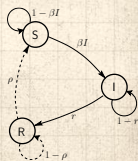
Model output

Nutshell

Other kinds of
prediction

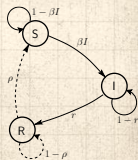
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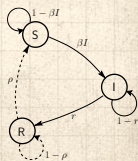
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