

Stochastic models:

Concepts and analysis

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Outline

Introduction

Describing a stochastic process

Equilibrium and quasi-equilibrium

Analytic methods

Conclusions

Modelling individual events

- ▶ Differential equations model continuous processes
- ▶ Disease spreads in the real world through discrete events
- ▶ Discrete events are fundamentally stochastic
 - ▶ Even in theory we don't know when the next event will occur, nor even what it will be

Types of stochasticity

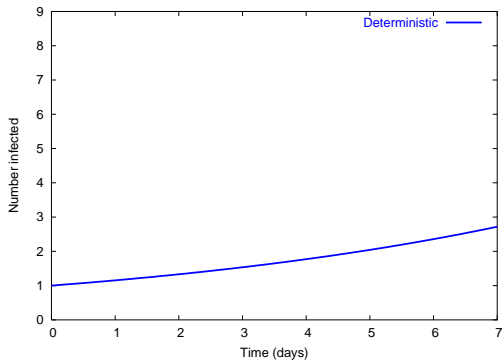
- ▶ Demographic stochasticity is caused by the existence of individual people and discrete events
- ▶ Environmental stochasticity refers to events that affect more than one person at a time
 - ▶ Weather
 - ▶ Politics
 - ▶ Economics

Modelling individual events

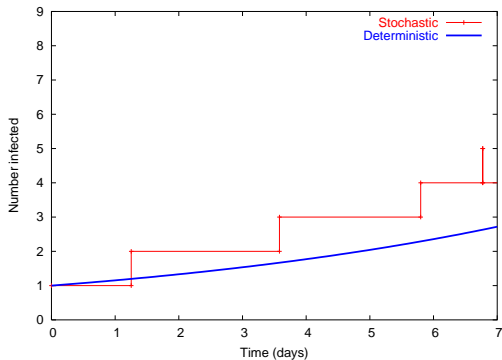


A stochastic potential-transmission event

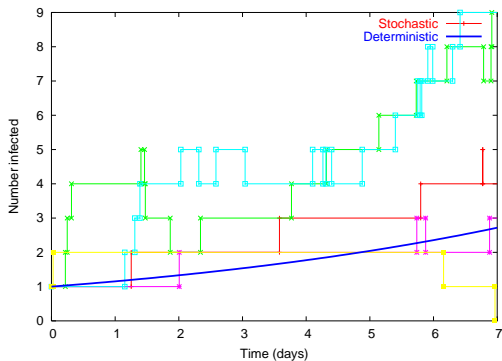
Deterministic spread



Demographic spread



Demographic spread



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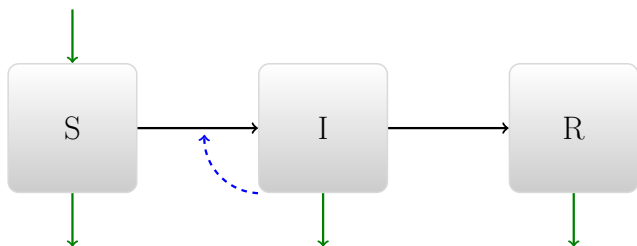
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States and rates

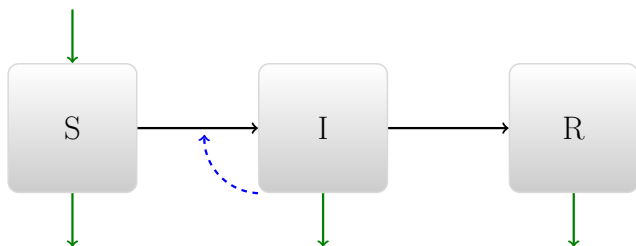
- ▶ We describe our system in terms of the *probability rates* of events happening
 - ▶ If the rate of event E is $r_E(t)$, the probability of the event occurring in the time interval $(t, t + dt)$ is $r_E(t)dt$
- ▶ If the system is *Markovian*, $r_E(t)$ depends only on the state of the system at time t
 - ▶ The Markovian assumption is convenient, but can have unwanted consequences

States and rates (Deterministic)



$$\begin{aligned}\frac{dS}{dt} &= \mu\hat{N} - \beta\frac{SI}{N} - \mu S \\ \frac{dI}{dt} &= \beta\frac{SI}{N} - \gamma I - \mu I\end{aligned}$$

States and rates (Demographic)



Event	transition	rate	Effect (S, I)
Infection	$S \rightarrow I$	$\beta SI/N$	$(-1, 1)$
Recovery	$I \rightarrow R$	γI	$(0, -1)$
Rebirth	$R \rightarrow S$	$\mu(N - S - I)$	$(1, 0)$
Rebirth	$I \rightarrow S$	μI	$(1, -1)$

Analogy

- ▶ The demographic model is an exact analogue of the deterministic one
 - ▶ Conceptually
 - ▶ In the limit as $N \rightarrow \infty$

Realizations and ensembles

- ▶ How do we think about the behavior of a stochastic process?
 - ▶ A single example of how the process could go (e.g., from a stochastic simulation) is called a *realization*
 - ▶ The universe of possible realizations is called the *ensemble*.
 - ▶ The probability distribution that describes what state we expect the population to be in at time t is called the *ensemble distribution*

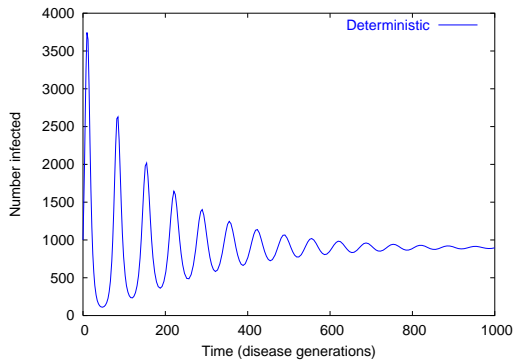
Some techniques

- ▶ Simulate one or many realizations
- ▶ Simulate the ensemble distribution
 - ▶ Requires one state variable for each possible state of the system
- ▶ Solve the ensemble distribution dynamics exactly!
 - ▶ Rarely possible
- ▶ Analytic approximations to the ensemble distribution

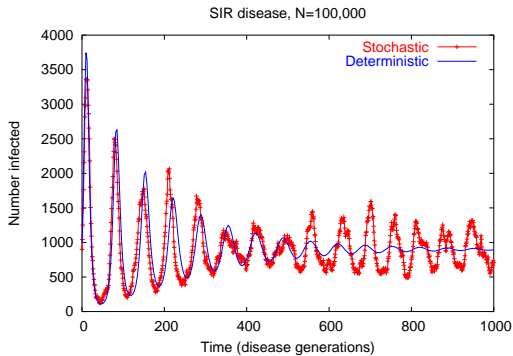
Simulating a realization

- ▶ Given a state of the system:
 - ▶ List possible events, and associated rates
 - ▶ Calculate the total rate r_T : this gives the rate at which the next event (whatever it is) will happen
 - ▶ i.e., an exponential waiting time with mean $1/r_T$
 - ▶ The probability of event E is r_E/r_T
 - ▶ Randomly select the time and nature of the next event
 - ▶ Change the system state appropriately
 - ▶ Repeat forever
 - ▶ Or until system is extinct
 - ▶ Or until you are tired

Deterministic model



Demographic model



Modelling the ensemble distribution

- ▶ We model the ensemble distribution by creating one conceptual 'box' for each possible state of the system, and asking what is the probability that the system is in each box.
 - ▶ This can be a lot of boxes
- ▶ The probabilities change as follows:
- ▶ $\dot{p}_S = \sum_{S'} p_{S'} r_{S' \rightarrow S} - p_S \sum_{S'} r_{S \rightarrow S'}$

Modelling the ensemble distribution

- ▶ If our system is small enough (particularly, if it has one state dimension) we might be able to simulate the ensemble distribution
- ▶ We might seek to solve these equations analytically
 - ▶ Only in special cases
- ▶ We might seek analytic approximations to increase our understanding
 - ▶ Moment approximations
 - ▶ Diffusion approximations

Questions

- ▶ What kind of questions do we want to ask with a stochastic model?
 - ▶ How does stochasticity affect disease dynamics?
 - ▶ Spatial distribution
 - ▶ Establishment
 - ▶ Persistence
 - ▶ How much variance do we expect stochasticity to cause?
 - ▶ Under what circumstances can we eliminate or eradicate a disease?

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Equilibrium

- ▶ Define equilibrium as an ensemble distribution that does not change with time
- ▶ What are the equilibria of our stochastic SIR system?
 - ▶ Disease free equilibrium
 - ▶ Others?
- ▶ There is no equilibrium corresponding to the endemic equilibrium of the deterministic system!
 - ▶ As long as any populations not extinct, proportion extinct will increase.

Quasi-equilibrium

- ▶ Consider the ensemble distribution confined to the subset of states where nothing is extinct
- ▶ This system can be described as a *fully connected* (you can get anywhere from anywhere else, *open* (you can leave the set) flow.
- ▶ Linear algebra tells us that such a system will converge to a stable *relative* distribution of probabilities of being in each non-extinct box

Interpreting the quasi-equilibrium

- ▶ The quasi-equilibrium is the asymptotic distribution of system states given that nothing has gone extinct
- ▶ The eigenvalue λ_q associated with the quasi-equilibrium distribution is the rate at which the probability of non-extinction decays (exponentially)
 - ▶ The distribution of persistence times must be asymptotically exponential
 - ▶ The expected persistence time (looking forward) approaches $-1/\lambda_q$ as the system continues to persist

Modelling the ensemble distribution

- ▶ We model the ensemble distribution by creating one conceptual 'box' for each possible state of the system, and asking what is the probability that the system is in each box.
 - ▶ This can be a lot of boxes
- ▶ The probabilities change as follows:
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Modelling the quasi-equilibrium

- ▶ We can also model the probability of being in a particular state given that extinction has not occurred
 - ▶ Computationally convenient
 - ▶ Can also keep track of cumulative extinction probability
- ▶ Define $q_S = p_S / (1 - p_N)$ where N is a 'null' state that we cannot escape from.
- ▶ Use quotient rule to find dynamic equations for q_S .

The fate of infectious disease

- ▶ Fizzle
 - ▶ Disease fails to “establish”
 - ▶ We will make this precise later
- ▶ Burn-out
 - ▶ Disease goes extinct after first epidemic
- ▶ Fade-out
 - ▶ Disease goes extinct after system approaches quasi-equilibrium
 - ▶ Can take a *long* time

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Linearization

- ▶ Two of the most useful tools for understanding deterministic disease models are linearizations:
 - ▶ **Disease-free equilibrium:** what factors control whether the disease can invade and persist?
 - ▶ **Endemic equilibrium:** tendency to cycle, damping or persistence of cycles
- ▶ Both of these methods have analogues in demographic models

Linear birth-death process

- ▶ We do an invasion analysis by asking how the number of infectives behaves in the limit where we assume that virtually the whole population is susceptible.
- ▶ This corresponds to a demographic model with the state determined by the number of infectious individuals I
- ▶ This system has only two events:
 - ▶ Infection at rate $R_0 I$
 - ▶ Recovery at rate I

Long-term behavior

- ▶ Unlike the finite systems discussed before, the probability of eventual extinction in this system is not one!
- ▶ Why not?
 - ▶ Probability of extinction given persistence goes to zero, as expected number of infectious individuals goes to ∞

Extinction probability

- ▶ Chains of infection are independent in this model
- ▶ We can use this fact to solve directly for the probability of extinction when starting from I infections, E_I
 - ▶ $E_I = R_0^{-I}$, when $R_0 > 1$
 - ▶ 1, otherwise
- ▶ We can define this as the ‘fizzle’ probability: the disease would have gone extinct even without depleting any susceptibles.

Moment calculations

- ▶ Ask: what is the expected behavior of the mean, variance, ... of the ensemble?
- ▶ Define: $\mu = \sum_I I p_I$
- ▶ How does μ change through time?
 - ▶ $\dot{\mu} = \sum_I I \dot{p}_I$
 - ▶ $= \sum_I (b_I - m_I) p_I$, where $b(I) = R_0 I$ is the 'birth' rate, and $m(I) = I$ is the 'death' rate
- ▶ These equations can be solved in the linear system, or approximated (by "moment closure") for non-linear systems

Diffusion approximations

- ▶ We can approximate the discrete-valued demographic system with a real-valued system that reflects the mean *and variance* of the demographic system
 - ▶ Thus we can incorporate demographic stochasticity in a continuous system
 - ▶ An excellent approximation except when some values are very small
- ▶ In a linear (or linearized) system, we can solve the equilibrium distribution of the continuous equations, and thus approximate the quasi-equilibrium distribution
 - ▶ Disease persistence
 - ▶ Size of demographic fluctuations

Diffusion approximations

- ▶ We linearize about the endemic equilibrium, in exact analogy to Jacobian methods for stability in deterministic models
- ▶ Diffusion (and thus demographic stochasticity) is relatively unimportant when the square of the number infected is large compared to the demographic variance
 - ▶ Number infected at equilibrium: $\frac{(R_0 - 1)\rho N}{R}$
 - ▶ $\approx \rho N$
 - ▶ Demographic variance: $\approx N$
- ▶ Diffusion index $\approx \rho^2 N$. If ρ is small, demographic stochasticity can be important even for very large populations.

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- ▶ Treating individuals as individuals can have dramatic effects on models of disease transmission
 - ▶ Acquired immunity is an important part of this phenomenon
- ▶ Stochastic models are hard, and we usually combine techniques to understand them:
 - ▶ Analytic approximation
 - ▶ Simulating ensemble distributions
 - ▶ Simulating realizations
- ▶ Remember: People are individuals \implies demographic stochasticity is real!



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