

A brief overview of further modeling approaches

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Author: Andreas Handel, Department of Epidemiology and Biostatistics, University of Georgia
ahandel@uga.edu

Types of mechanistic, dynamical models

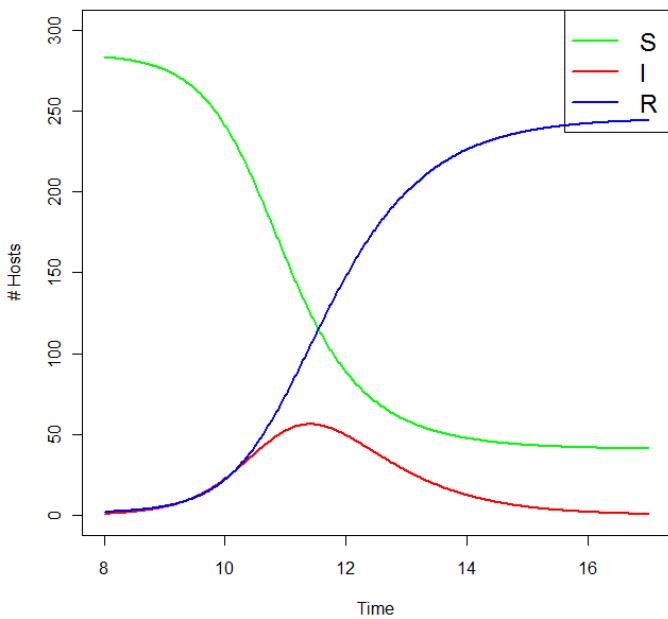
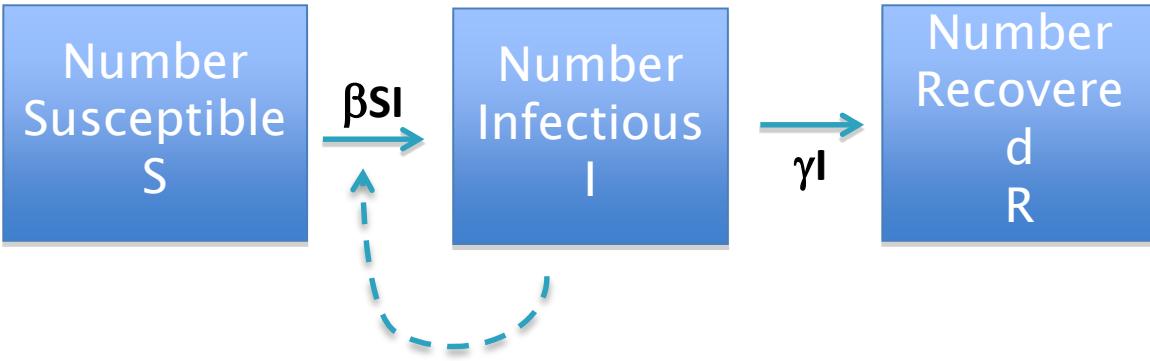
- ▶ Because infection processes describe changes in time, **dynamical, mechanistic models** are widely used.
- ▶ Such models can be formulated in many different ways. A few possible classifications are:
 - Compartmental ↔ Agent-based
 - Discrete time ↔ continuous time
 - Deterministic ↔ Stochastic
 - Space-less (homogeneous) ↔ Spatial
 - Memory-less (Markov) ↔ with memory
 - Small ↔ Big
 - Data-free ↔ With data

Compartmental versus Agent/Individual based models

Compartmental models

- ▶ The components of the model are treated as homogeneous groups (compartments), one only tracks population numbers/sizes
- ▶ The simplest type of model, sometimes mathematically tractable, easy to implement on a computer
- ▶ Good model for fitting data
- ▶ The assumption that populations are homogeneous and “well mixed” is always wrong (but sometimes it is a good enough approximation)
- ▶ Often the best starting point

Compartmental models - Examples



$$\dot{S} = -\beta SI$$

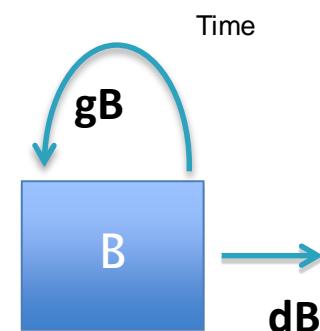
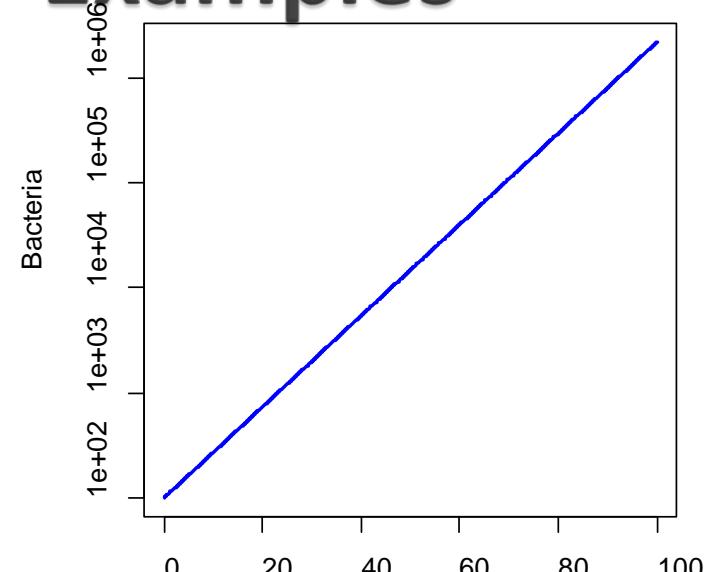
$$\dot{I} = \beta SI - \gamma I$$

$$\dot{R} = \gamma I$$

$$S_{t+\tau} = S_t - (\beta S_t I_t) \tau$$

$$I_{t+\tau} = I_t + (\beta S_t I_t - \gamma I_t) \tau$$

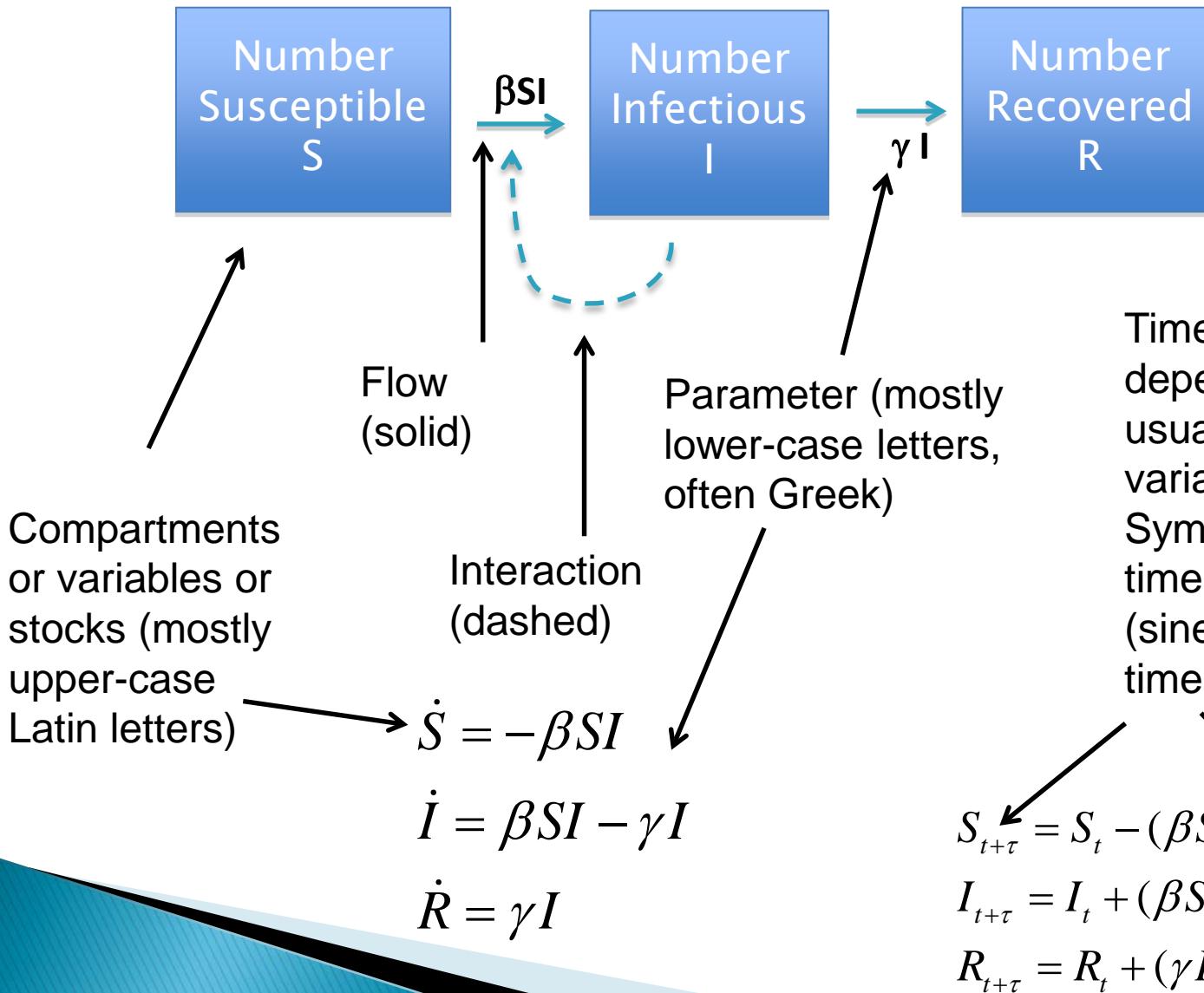
$$R_{t+\tau} = R_t + (\gamma I_t) \tau$$



$$\dot{B} = gB - dB$$

$$B_{t+\tau} = B_t + (gB - dB) \tau$$

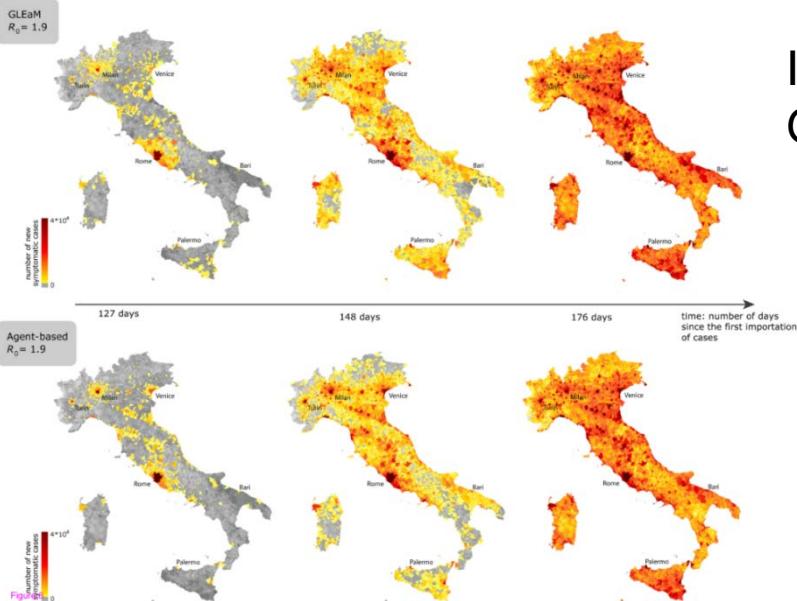
(Compartmental) models - Terminology



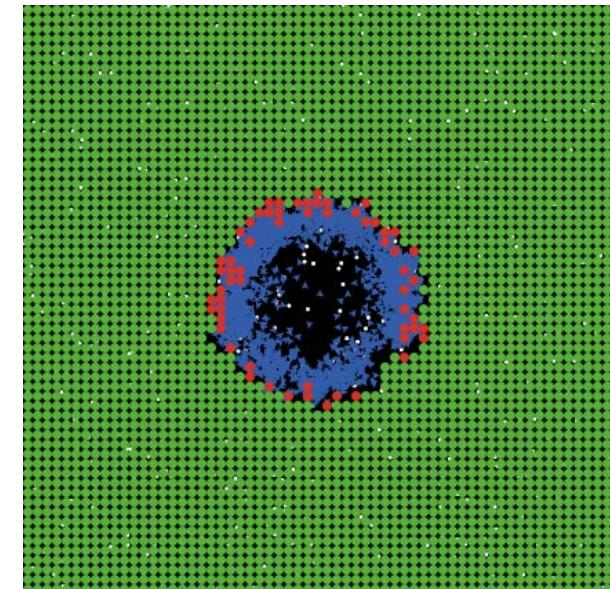
Individual/agent based models

- ▶ Every unit/host/individual is modeled/tracked. Called agent-based or individual-based models (ABM/IBM).
- ▶ Mostly computational, (almost) no mathematical analysis is possible.
- ▶ One can't easily write down a set of equations, though one can specify a set of rules.
- ▶ ABM usually have many parameters.
- ▶ ABM take long to run
- ▶ ABM are difficult to fit to data
- ▶ ABM are potentially most detailed and realistic

Individual based models - examples

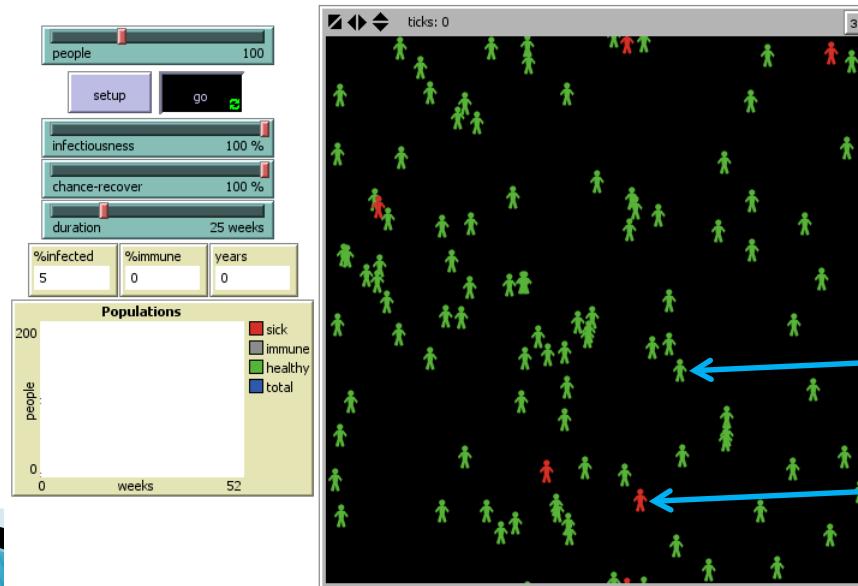


Influenza in Italy:
Gleamviz.org



Influenza
infection inside a
host

NetLogo
outbreak
example

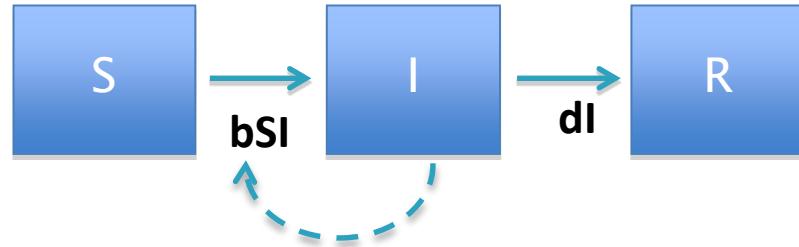
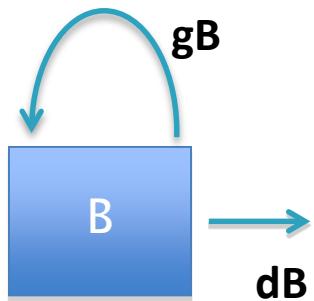


Discrete time versus continuous time models

Discrete time models

- ▶ The system is updated in discrete time-steps.
- ▶ Good for systems where there is a “natural” time step
 - Example: Some pathogens have a more-or-less fixed replication cycle (e.g. $\approx 24\text{h}$ for *Plasmodium falciparum*).
 - Example: For some animals, births occur during a small period in spring. Modeling the long-term dynamics of an ID in such a population might lend itself to a model that is updated annually.
- ▶ Complex models, such as Agent-based simulations are almost always discrete-time (for computational reasons).
- ▶ Discrete-time compartmental models are often formulated as difference equations.
- ▶ If the time-step becomes small, a discrete-time model approaches a continuous-time model.

Discrete time models - Examples

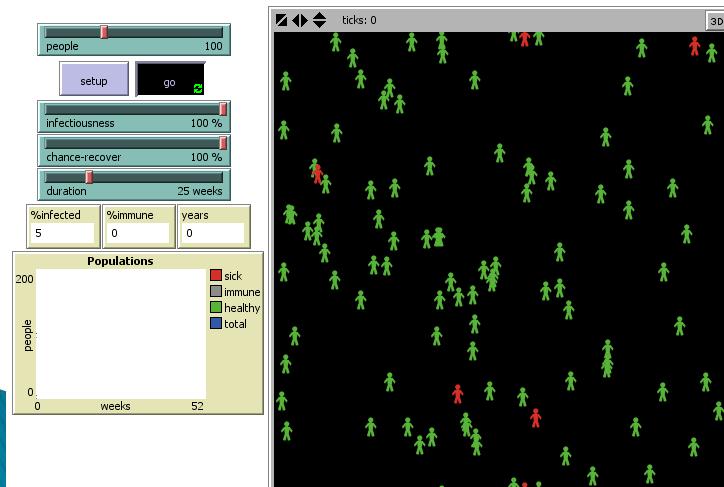


$$B_{t+\tau} = B_t + (gB - dB)\tau$$

$$S_{t+\tau} = S_t - (bS_t I_t) \tau$$

$$I_{t+\tau} = I_t + (bS_t I_t - dI_t) \tau$$

$$R_{t+\tau} = R_t + (dI_t) \tau$$



Continuous time models

- ▶ The system is updated continuously.
- ▶ Best for systems where changes occur continuously and concurrently.
 - Example: To model births and deaths of bacteria in a large population, with new birth and recoveries occurring continuously and concurrently, a continuous-time model might be best.
 - Example: To model an outbreak of flu (or some other ID) in a large population, with new infections and recoveries occurring continuously and concurrently, a continuous-time model might be best.
- ▶ Continuous-time models are usually described by differential equations.
- ▶ Ordinary differential equation (ODE) models are the most common and simplest one.

Ordinary Differential Equations (ODE)

- ▶ ODEs can be derived as the continuum limit of discrete models:

$$B_{t+\tau} = B_t + (gB - dB)\tau \quad \xrightarrow{\text{rewrite}} \quad \frac{B_{t+\tau} - B_t}{\tau} = (gB - dB)$$

$$\frac{B_{t+\tau} - B_t}{\tau} = (gB - dB) \quad \xrightarrow{\tau \rightarrow 0} \quad \frac{dB(t)}{dt} = gB(t) - dB(t)$$

or

$$\dot{B} = gB - dB$$

Ordinary Differential Equations (ODE)

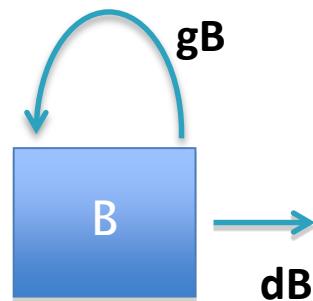
- Often, ODEs are derived as the continuum limit of discrete models:

The computer uses this

$$B_{t+\tau} = B_t + (gB - dB)\tau$$

We often can/could do math with this

$$\dot{B} = gB - dB$$



Same flow diagram for both models

Ordinary Differential Equations (ODE)

- ▶ ODEs can be derived as the continuum limit of discrete models:

$$S_{t+\tau} = S_t - (\beta S_t I_t) \tau$$

$$I_{t+\tau} = I_t + (\beta S_t I_t - \gamma I_t) \tau$$

$$R_{t+\tau} = R_t + (\gamma I_t) \tau$$

rewrite
→

$$\frac{S_{t+\tau} - S_t}{\tau} = -\beta S_t I_t$$

$$\frac{I_{t+\tau} - I_t}{\tau} = \beta S_t I_t - \gamma I_t$$

$$\frac{R_{t+\tau} - R_t}{\tau} = \gamma I_t$$

$$\frac{S_{t+dt} - S_t}{dt} = -\beta S_t I_t$$

rename
→ $\frac{I_{t+dt} - I_t}{dt} = \beta S_t I_t - \gamma I_t$

$$\frac{R_{t+dt} - R_t}{dt} = \gamma I_t$$

Reduce
 $dt \rightarrow 0$
→

$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dI}{dt} = \beta SI - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

Ordinary Differential Equations (ODE)

- Often, ODEs are derived as the continuum limit of discrete models:

The computer uses this

$$S_{t+\tau} = S_t - (\beta S_t I_t) \tau$$

$$I_{t+\tau} = I_t + (\beta S_t I_t - \gamma I_t) \tau$$

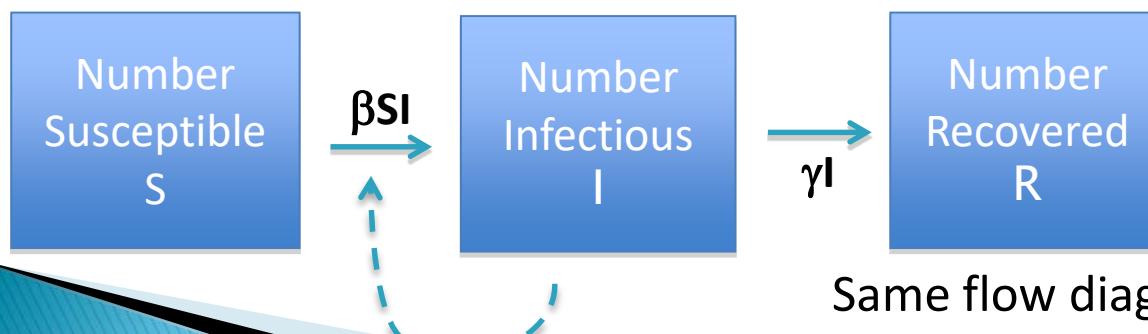
$$R_{t+\tau} = R_t + (\gamma I_t) \tau$$

We often can/could do math with this

$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dI}{dt} = \beta SI - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$



Same flow diagram for both models

Continuous time models - Notation

$$\frac{dS(t)}{dt} = -bS(t)I(t)$$

$$\frac{dI(t)}{dt} = bS(t)I(t) - dI(t)$$

$$\frac{dR(t)}{dt} = dI(t)$$

$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dI}{dt} = \beta SI - \gamma I$$

$$\dot{S} = -\beta SI$$

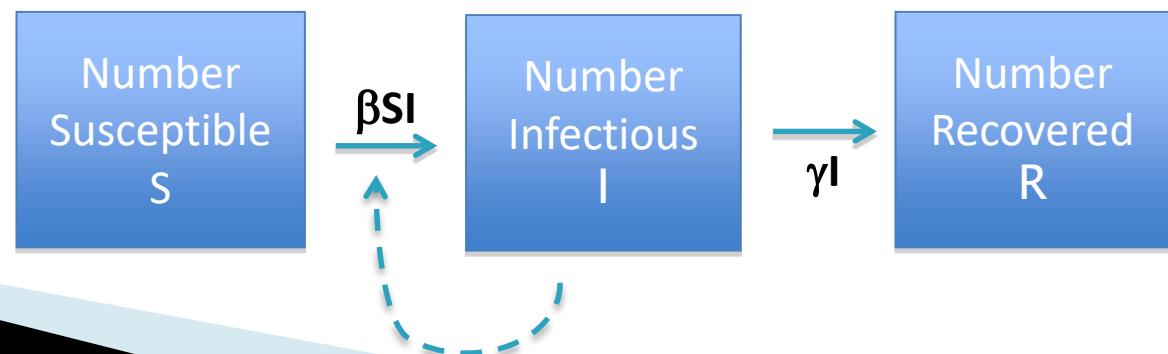
$$\dot{I} = \beta SI - \gamma I$$

$$\dot{R} = \gamma I$$

$$\frac{dR}{dt} = \gamma I$$

LHS is the (instantaneous) change in a variable/compartment

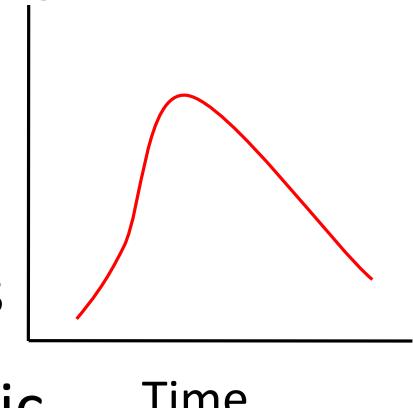
RHS explains how the variable on the LHS increases (positive terms) or decreases (negative terms)



Deterministic versus stochastic models

Deterministic models

- ▶ For given parameters and initial conditions, the model always produces the same result
- ▶ Simple, easy to implement on a computer
- ▶ Sometimes one can do analytical calculations
- ▶ Real biological systems are never deterministic, but sometimes approximately so
- ▶ When large numbers are involved, deterministic models tend to be good. They break down when only few entities (e.g. few hosts) are involved



Deterministic models - examples



$$S_{t+\tau} = S_t - (bS_t I_t) \tau$$

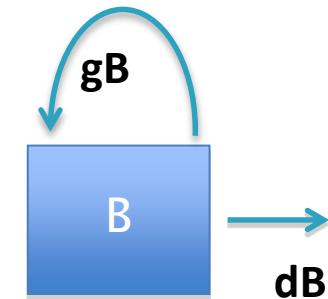
$$I_{t+\tau} = I_t + (bS_t I_t - dI_t) \tau$$

$$R_{t+\tau} = R_t + (dI_t) \tau$$

$$\dot{S} = -bSI$$

$$\dot{I} = bSI - dI$$

$$\dot{R} = dI$$

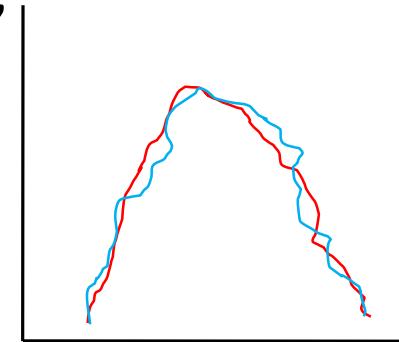


$$\dot{B} = gB - dB$$

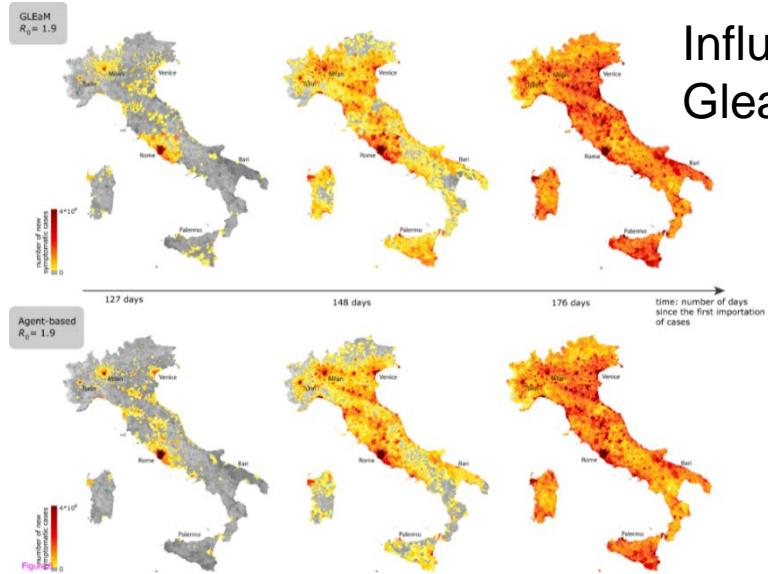
$$B_{t+\tau} = B_t + (gB - dB) \tau$$

Stochastic models

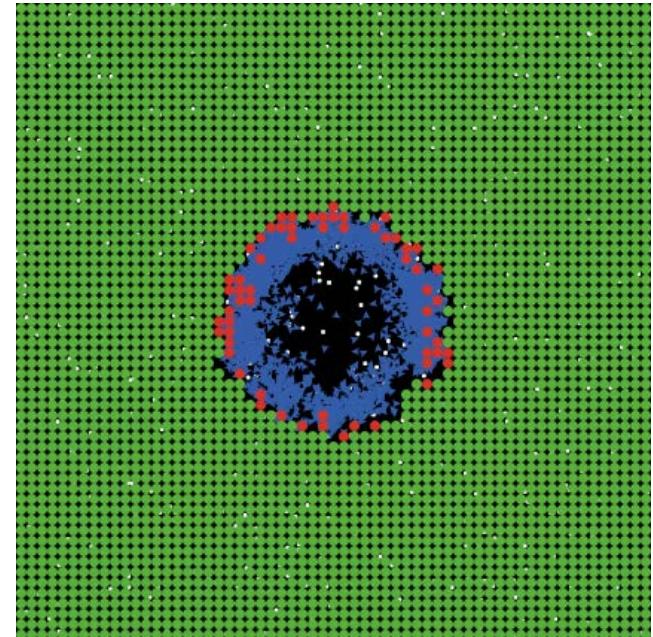
- ▶ Results differ between simulations, even for the same model conditions.
- ▶ More difficult to implement on a computer, takes longer to run.
- ▶ The math is more difficult.
- ▶ Closer to the “real” system.
- ▶ Stochastic effects are important at low numbers.
- ▶ The same model implemented as deterministic or stochastic can lead to different results!



Stochastic models - examples



Influenza in Italy:
Gleamviz.org



$$S_{t+\tau} = S_t - (\beta S_t I_t) \tau$$

$$I_{t+\tau} = I_t + (\beta S_t I_t - \gamma I_t) \tau + \text{Noise}$$

$$R_{t+\tau} = R_t + (\gamma I_t) \tau$$

Influenza infection inside a host

$$B_{t+\tau} = B_t + (gB - dB) \tau + \text{Noise}$$

Homogeneous/space-less versus spatial models

Homogeneous/space-less models

- ▶ There is no explicit notion of space. Entities (e.g. hosts) are assumed to exist in a homogenous space.
- ▶ Entities are assumed to be well-mixed and randomly bump into each other.
- ▶ Most compartmental models make this assumption.

Space-less models - examples



$$S_{t+\tau} = S_t - (bS_t I_t) \tau$$

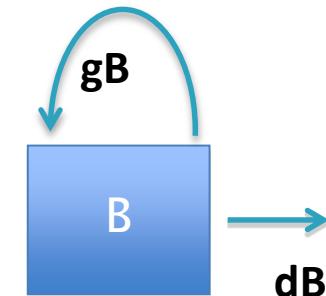
$$I_{t+\tau} = I_t + (bS_t I_t - dI_t) \tau$$

$$R_{t+\tau} = R_t + (dI_t) \tau$$

$$\dot{S} = -bSI$$

$$\dot{I} = bSI - dI$$

$$\dot{R} = dI$$

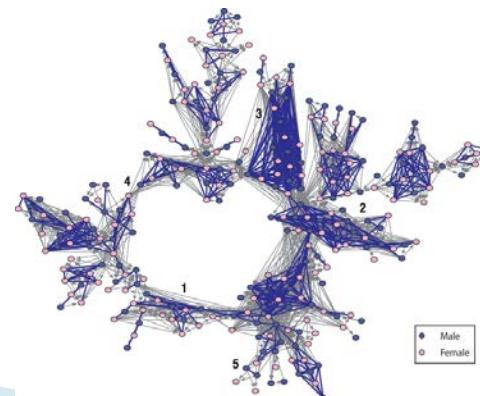
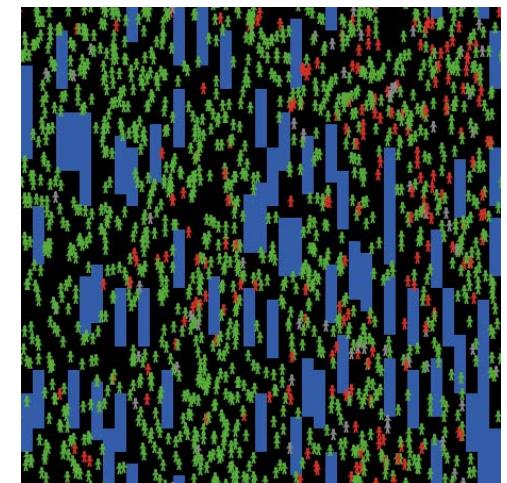
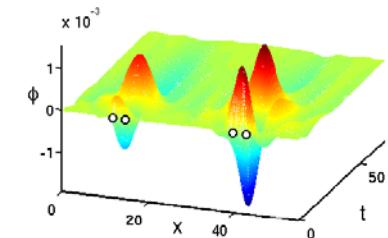


$$\dot{B} = gB - dB$$

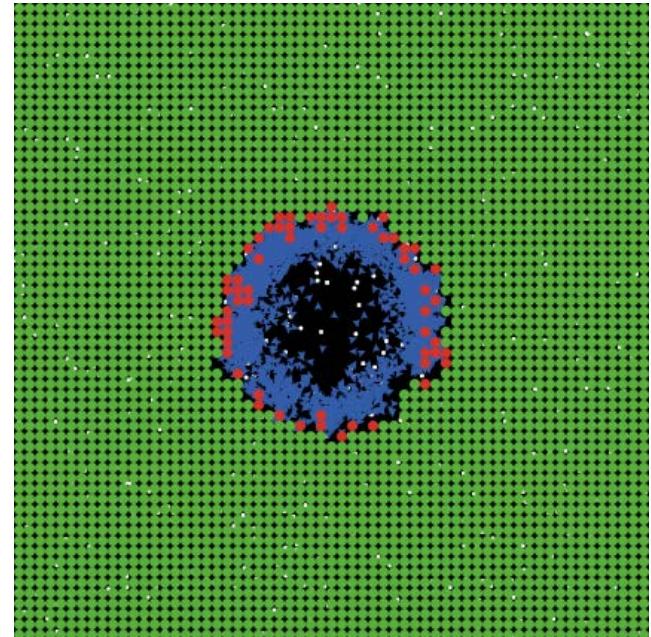
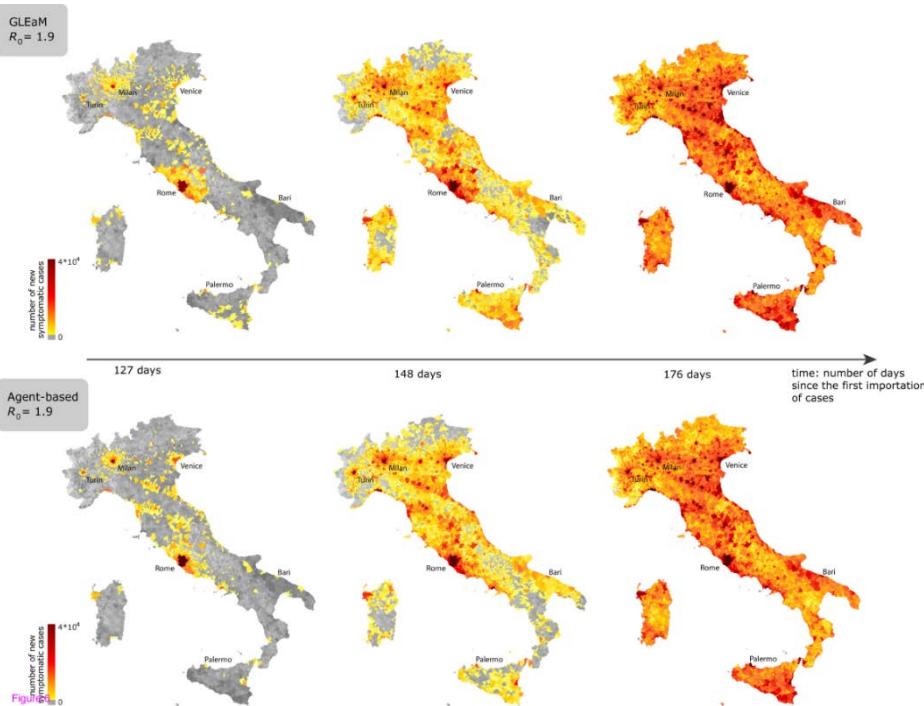
$$B_{t+\tau} = B_t + (gB - dB) \tau$$

Spatial models

- ▶ Some notion of space is explicitly included.
- ▶ Different types of models can be used:
 - Partial Differential equations.
 - Patch/Meta-population models. Usually coupling of multiple compartmental models.
 - Agent-based models.
 - Network models.

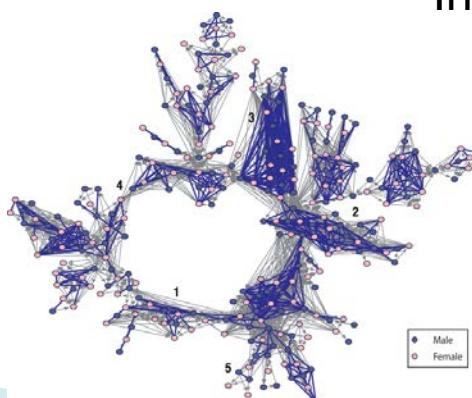


Spatial models - Examples



Influenza in Italy:
Gleamviz.org

Influenza infection inside a host

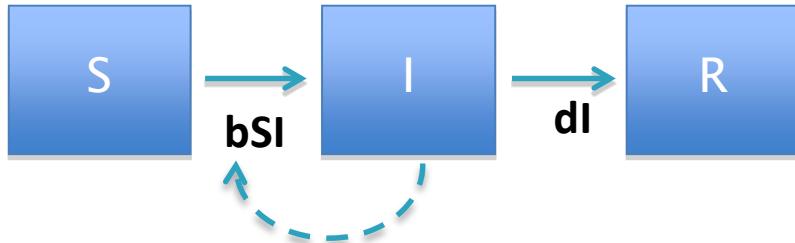


Memory-less (Markov) models versus models with memory

Memory-less models

- ▶ Many models (e.g. those based on ordinary differential equations, ODE) are memory-less (markovian). That means what happens next in the system only depends on the **current** state of the system, not on the past.
- ▶ That means for instance that an infected individual has an equal chance to recover at any time, no matter how long ago the infection occurred.
- ▶ This approximation is sometimes, but not always acceptable.

Memory-less models - examples



$$S_{t+\tau} = S_t - (bS_t I_t) \tau$$

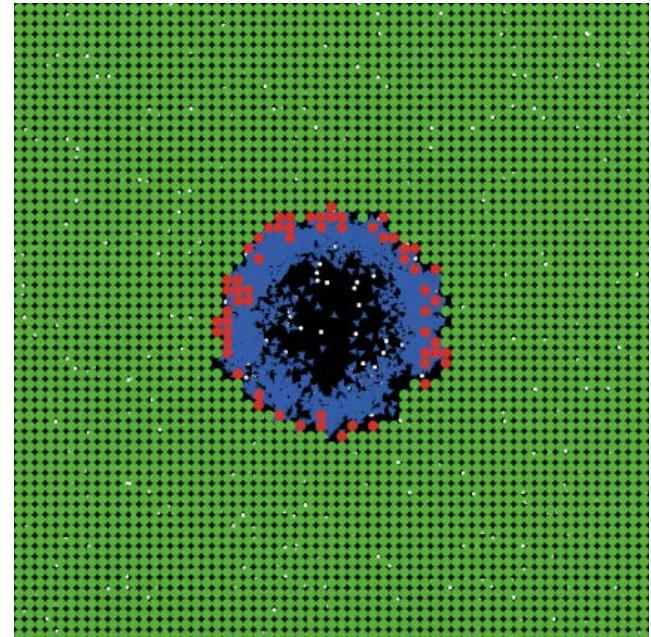
$$I_{t+\tau} = I_t + (bS_t I_t - dI_t) \tau$$

$$R_{t+\tau} = R_t + (dI_t) \tau$$

$$\frac{dS(t)}{dt} = -bS(t)I(t)$$

$$\frac{dI(t)}{dt} = bS(t)I(t) - dI(t)$$

$$\frac{dR(t)}{dt} = dI(t)$$



Depends on how the ABM is implemented.

Models with memory

- ▶ If we want to keep track of the past, e.g. if we want to let the chance of recovery depend on the time since infection, we can't use ODE models.
- ▶ We need models that keep track of the past, i.e. that are non-markovian.
- ▶ Possible models:
 - Partial differential equations
 - Delay differential equations
 - Agent-based models
 - ODE models with “dummy compartments”

Models with memory - examples

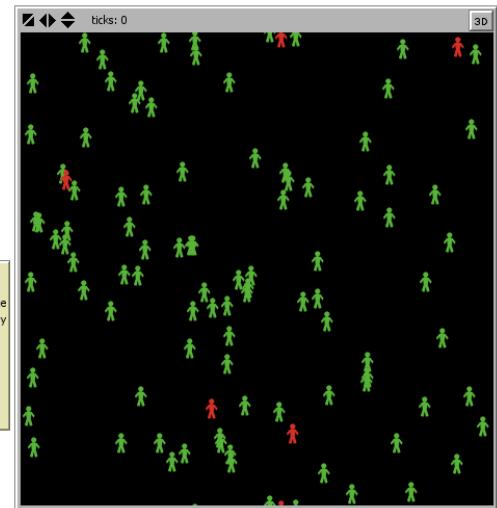
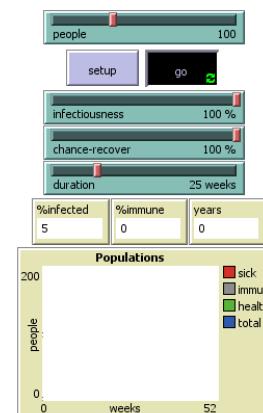
Delay differential equation (DDE)

$$\frac{dS(t)}{dt} = -\beta S(t)I(t - \tau)$$

$$\frac{dI(t)}{dt} = \beta S(t)I(t - \tau) - \gamma I(t)$$

$$\frac{dR(t)}{dt} = \gamma I(t)$$

delay



Depends on how the ABM is implemented.

Partial differential equation (PDE)

$$\frac{\partial I(t, a)}{\partial t} = -\gamma(a)I(t, a) - \frac{\partial I(t, a)}{\partial a}$$

Recovery depends on age since infection

Age since infection

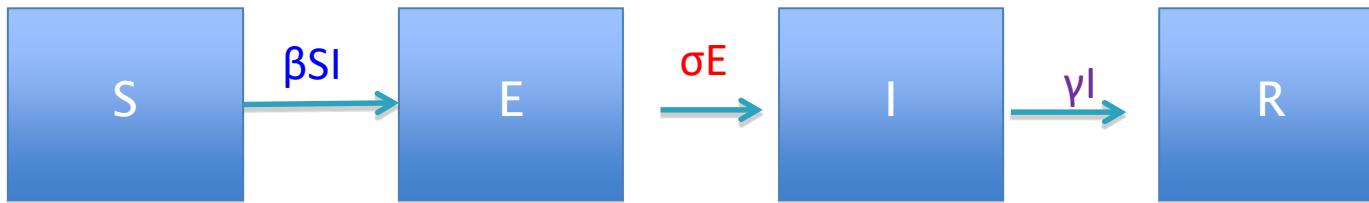
“aging” of infecteds

**Small/simple
versus
large/complex
models**

Small models

- ▶ Start with a very simple model, try to capture the most important aspects of the known dynamics of the system.
- ▶ Analyze model to gain conceptual insights. It should be relatively easy to understand what is going on.
- ▶ It's often possible to fit the model to data. Model rejection (e.g. poor agreement with data) is helpful, it taught us something.
- ▶ The model might not include crucial known biology and therefore the insights/results might be of limited use (or completely useless).

Small models - examples

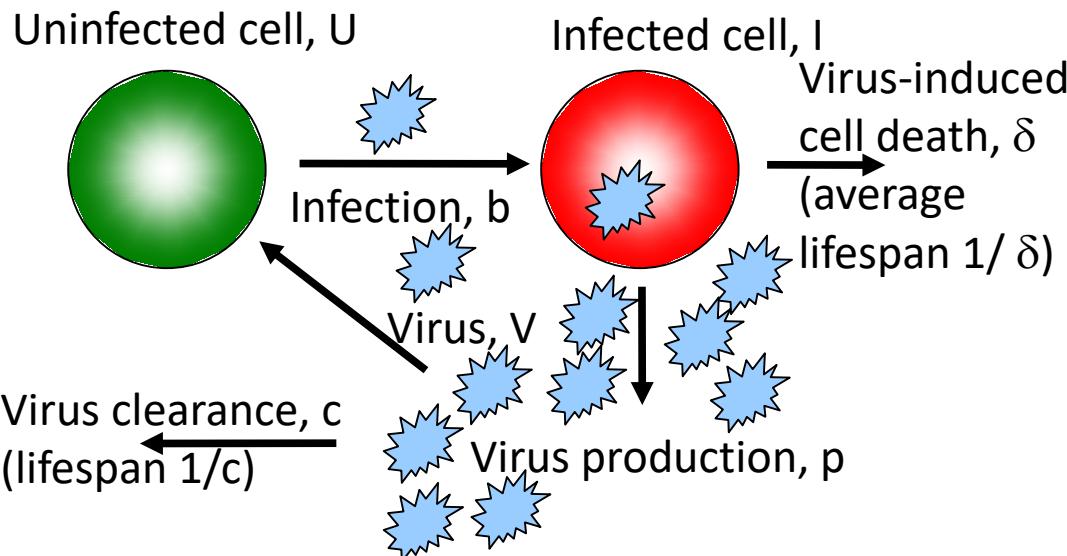


$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dE}{dt} = \beta SI - \sigma E$$

$$\frac{dI}{dt} = \sigma E - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$



$$\dot{U} = -bUV \quad (\text{uninfected cells})$$

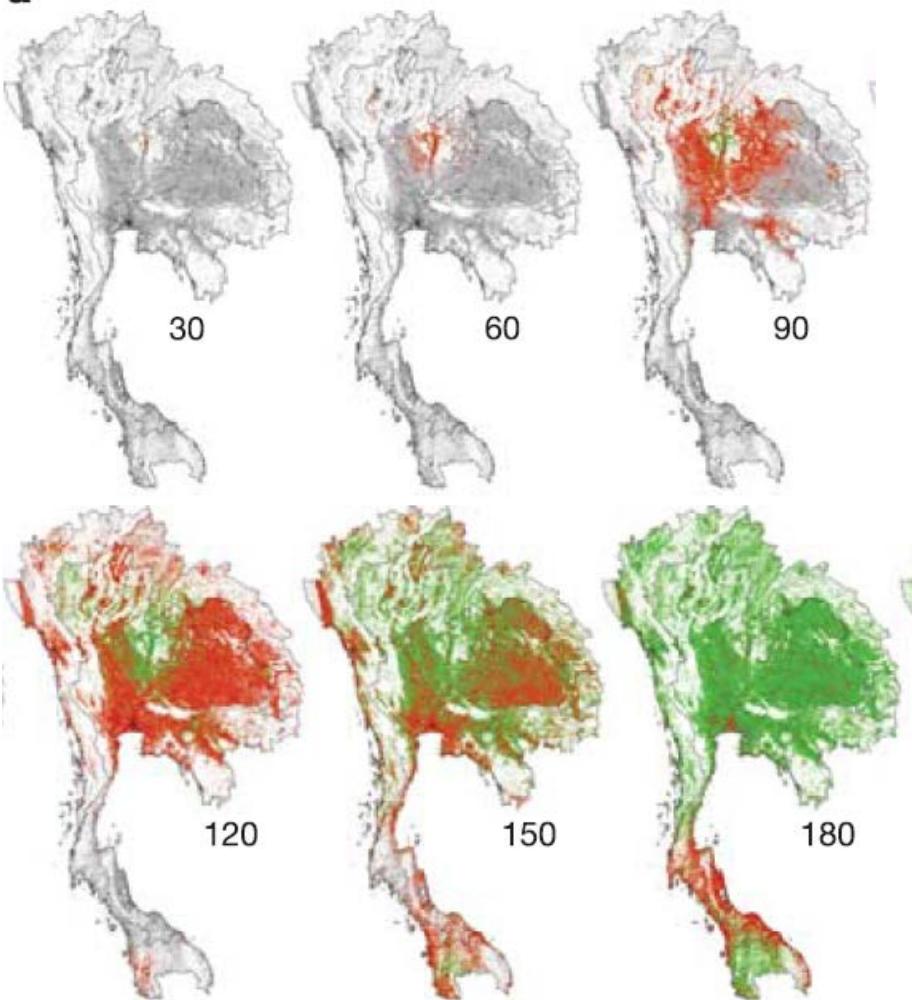
$$\dot{I} = bUV - \delta I \quad (\text{infected cells})$$

$$\dot{V} = pI - cV \quad (\text{free virus})$$

Big models

- ▶ Build a comprehensive model, try to include a lot of detail.
- ▶ Run the model on the computer, investigate results. It's often hard to understand how the different components of the model influence the result. Careful analysis is needed.
- ▶ Model results that are at odds with known biology can suggest needed model modifications. But big models can reproduce a lot of observed phenomena, even if the model is wrong.
- ▶ Data fitting is usually not possible, seldom is enough data available. Without fitting, model can rarely be formally rejected.
- ▶ Comprehensive and accurate models can be used to make detailed, quantitative predictions.

Big models - examples



Ferguson et al, 2005 Nature

$$\begin{aligned}
 \lambda_{ii} &= \beta_{u,n}I_{u,n} + \beta_{u,p}I_{u,p} + \beta_{t,n}I_{t,n} + \beta_{t,p}I_{t,p} \\
 \lambda_{bi} &= \alpha_{u,u}B_{u,u} + \alpha_{u,t}B_{u,t} + \alpha_{t,u}B_{t,u} + \alpha_{t,t}B_{t,t} \\
 \lambda_1 &= \lambda_{ii} + \lambda_{bi} \\
 \lambda_{bb} &= \gamma_{u,u}B_{u,u} + \gamma_{u,t}B_{u,t} + \gamma_{t,u}B_{t,u} + \gamma_{t,t}B_{t,t} \\
 \lambda_{ib} &= \kappa_{u,n}I_{u,n} + \kappa_{u,p}I_{u,p} + \kappa_{t,n}I_{t,n} + \kappa_{t,p}I_{t,p} \\
 \lambda_2 &= \lambda_{bb} + \lambda_{ib} \\
 \dot{S} &= -\lambda_1(1 - e_p f_p)S \\
 \dot{I}_{u,n} &= (1 - g_p)(1 - f_t)(1 - f_p)\lambda_1 S - v_{u,n}I_{u,n} - k_{u,n}\lambda_2 I_{u,n} \\
 \dot{I}_{u,p} &= g_p(1 - f_t)(1 - f_p)\lambda_1 S - v_{u,p}I_{u,p} - k_{u,p}\lambda_2 I_{u,p} \\
 \dot{I}_{t,n} &= (1 - g_p)(f_t(1 - f_p) + f_p(1 - e_p))\lambda_1 S - v_{t,n}I_{t,n} - k_{t,n}\lambda_2 I_{t,n} \\
 \dot{I}_{t,p} &= g_p(f_t(1 - f_p) + f_p(1 - e_p))\lambda_1 S - v_{t,p}I_{t,p} - k_{t,p}\lambda_2 I_{t,p} \\
 \dot{B}_{u,u} &= (1 - f_t)(1 - g_t)(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} - \delta_{u,u}B_{u,u} \\
 \dot{B}_{u,t} &= (1 - f_t)g_t(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} \\
 &\quad + (1 - f_t)(v_{u,p}c_{u,p} + k_{u,p}\lambda_2)I_{u,p} - \delta_{u,t}B_{u,t} \\
 \dot{B}_{t,u} &= f_t(1 - g_t)(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} \\
 &\quad + (1 - g_t)(v_{t,n}c_{t,n} + k_{t,n}\lambda_2)I_{t,n} - \delta_{t,u}B_{t,u} \\
 \dot{B}_{t,t} &= f_tg_t(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} + f_t(v_{u,p}c_{u,p} + k_{u,p}\lambda_2)I_{u,p} \\
 &\quad + g_t(v_{t,n}c_{t,n} + k_{t,n}\lambda_2)I_{t,n} + (v_{t,p}c_{t,p} + k_{t,p}\lambda_2)I_{t,p} - \delta_{t,t}B_{t,t}
 \end{aligned}$$

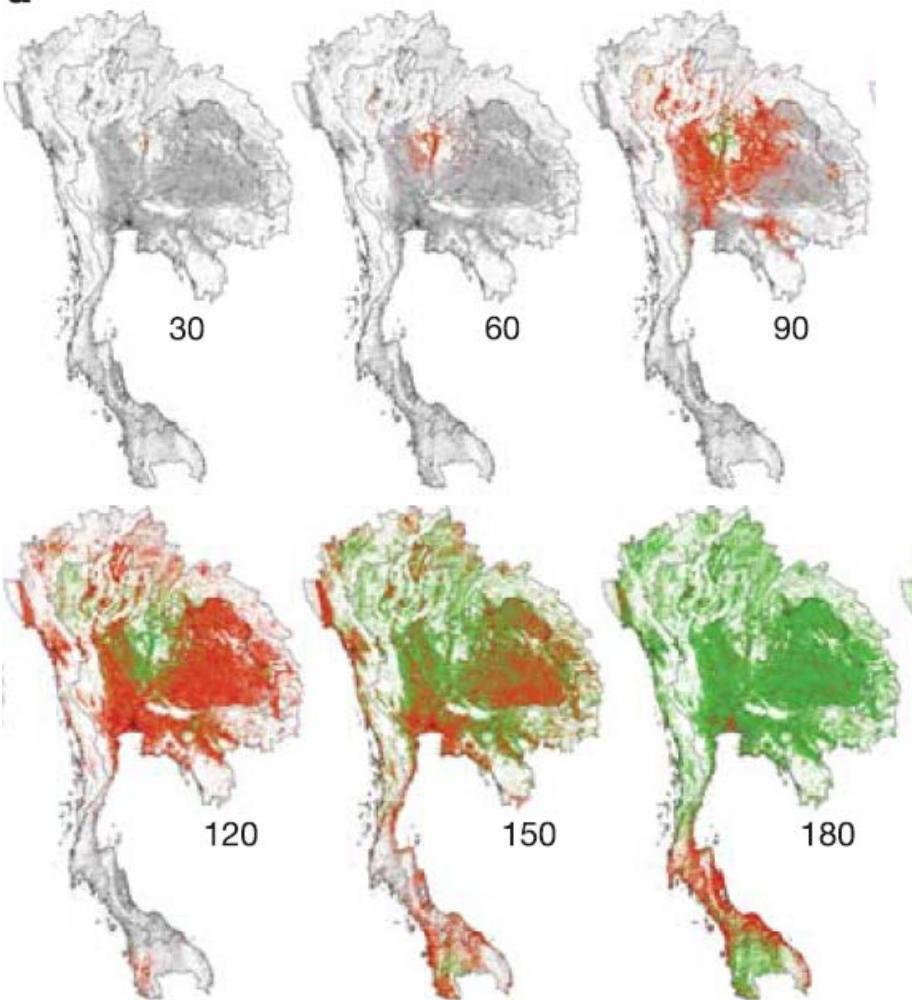
Handel et al, 2009
Epidemics

Data-free models versus models with data

Data-free

- ▶ Model is formulated and model parameters are chosen based on known biology.
- ▶ Model should be “data-driven”, i.e. based on what is known about the system.
- ▶ Model is analyzed “by itself”, i.e. without trying to perform inference and rigorously fit it to data.
- ▶ Relatively easy to do. Can produce useful insights even if only limited data are available.

Data-free – examples



Ferguson et al, 2005 Nature

$$\begin{aligned}
 \lambda_{ii} &= \beta_{u,n}I_{u,n} + \beta_{u,p}I_{u,p} + \beta_{t,n}I_{t,n} + \beta_{t,p}I_{t,p} \\
 \lambda_{bi} &= \alpha_{u,u}B_{u,u} + \alpha_{u,t}B_{u,t} + \alpha_{t,u}B_{t,u} + \alpha_{t,t}B_{t,t} \\
 \lambda_1 &= \lambda_{ii} + \lambda_{bi} \\
 \lambda_{bb} &= \gamma_{u,u}B_{u,u} + \gamma_{u,t}B_{u,t} + \gamma_{t,u}B_{t,u} + \gamma_{t,t}B_{t,t} \\
 \lambda_{ib} &= \kappa_{u,n}I_{u,n} + \kappa_{u,p}I_{u,p} + \kappa_{t,n}I_{t,n} + \kappa_{t,p}I_{t,p} \\
 \lambda_2 &= \lambda_{bb} + \lambda_{ib} \\
 \dot{S} &= -\lambda_1(1 - e_p f_p)S \\
 \dot{I}_{u,n} &= (1 - g_p)(1 - f_t)(1 - f_p)\lambda_1 S - v_{u,n}I_{u,n} - k_{u,n}\lambda_2 I_{u,n} \\
 \dot{I}_{u,p} &= g_p(1 - f_t)(1 - f_p)\lambda_1 S - v_{u,p}I_{u,p} - k_{u,p}\lambda_2 I_{u,p} \\
 \dot{I}_{t,n} &= (1 - g_p)(f_t(1 - f_p) + f_p(1 - e_p))\lambda_1 S - v_{t,n}I_{t,n} - k_{t,n}\lambda_2 I_{t,n} \\
 \dot{I}_{t,p} &= g_p(f_t(1 - f_p) + f_p(1 - e_p))\lambda_1 S - v_{t,p}I_{t,p} - k_{t,p}\lambda_2 I_{t,p} \\
 \dot{B}_{u,u} &= (1 - f_t)(1 - g_t)(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} - \delta_{u,u}B_{u,u} \\
 \dot{B}_{u,t} &= (1 - f_t)g_t(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} \\
 &\quad + (1 - f_t)(v_{u,p}c_{u,p} + k_{u,p}\lambda_2)I_{u,p} - \delta_{u,t}B_{u,t} \\
 \dot{B}_{t,u} &= f_t(1 - g_t)(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} \\
 &\quad + (1 - g_t)(v_{t,n}c_{t,n} + k_{t,n}\lambda_2)I_{t,n} - \delta_{t,u}B_{t,u} \\
 \dot{B}_{t,t} &= f_tg_t(v_{u,n}c_{u,n} + k_{u,n}\lambda_2)I_{u,n} + f_t(v_{u,p}c_{u,p} + k_{u,p}\lambda_2)I_{u,p} \\
 &\quad + g_t(v_{t,n}c_{t,n} + k_{t,n}\lambda_2)I_{t,n} + (v_{t,p}c_{t,p} + k_{t,p}\lambda_2)I_{t,p} - \delta_{t,t}B_{t,t}
 \end{aligned}$$

Handel et al, 2009
Epidemics

With data

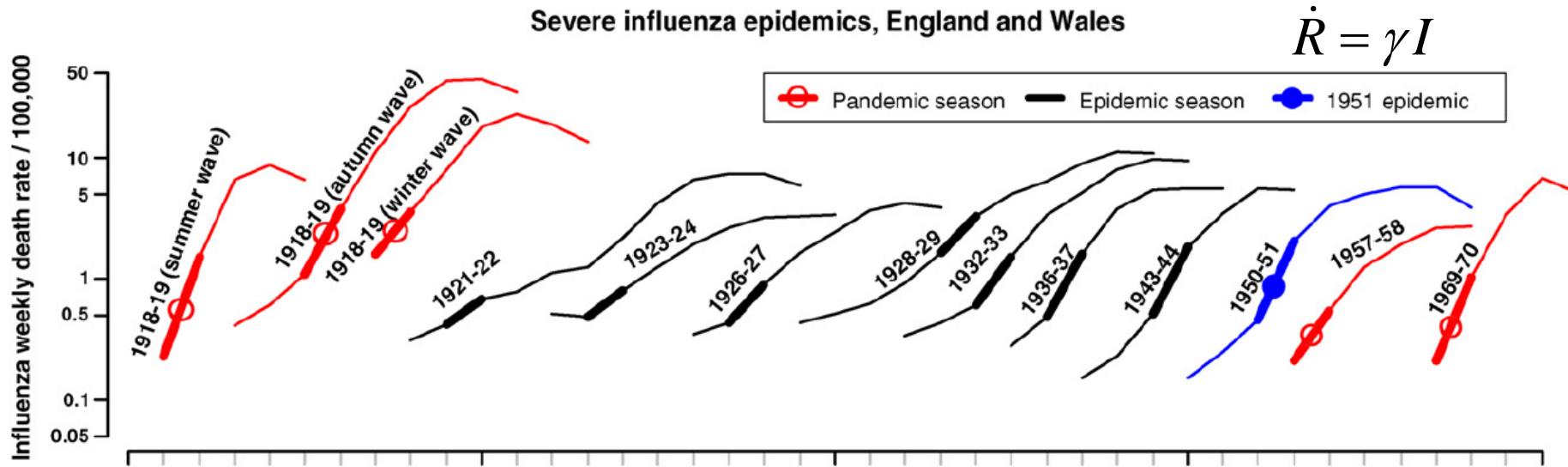
- ▶ Models are being fitted to data (inference).
- ▶ Rigorous comparison of models with data.
- ▶ Used to discriminate hypotheses, determine parameters.
- ▶ Less flexibility in model formulation, often constrained/determined by available data.

With data – examples

$$\dot{S} = -\beta SI$$

$$\dot{I} = \beta SI - \gamma I$$

$$\dot{R} = \gamma I$$

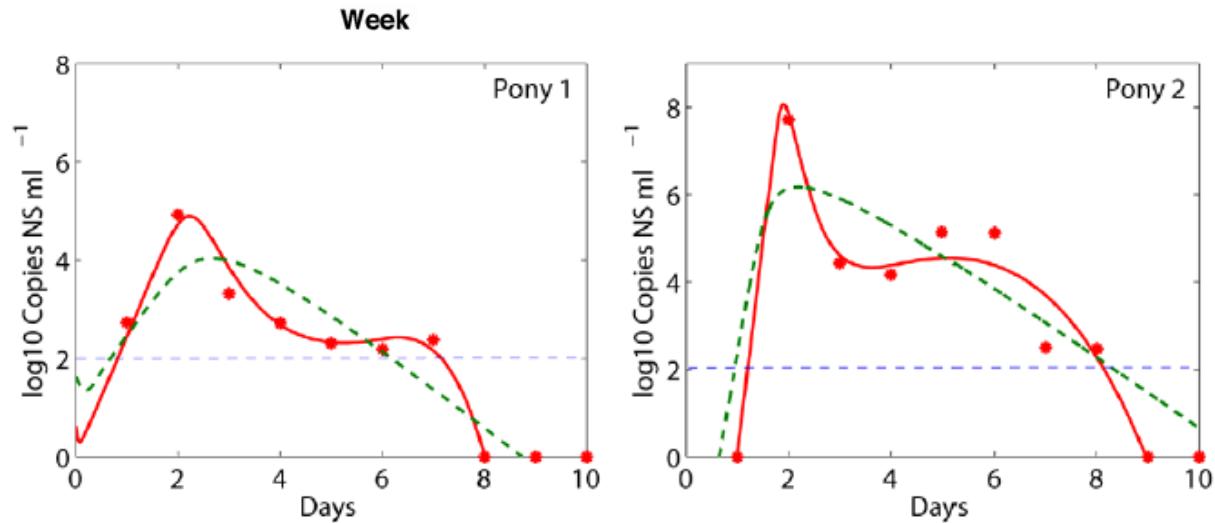


Viboud et al, 2006
Vaccine

$$\dot{U} = -bUV$$

$$\dot{I} = bUV - \delta I$$

$$\dot{V} = pI - cV$$



Pawelek et al, 2012 PLoS Comp Bio

Types of models

- ▶ Models have several of the different characteristics just described. Examples:
 - Deterministic, compartmental, continuous time, no-memory, no-space, small model – i.e. a set of ODEs (very common).
 - Deterministic, agent-based, no-space, no-memory (very rare)
- ▶ Ideal approach: Choose the model that is most suitable for the question you try to answer.
- ▶ In reality: Model selection is based on a mix of
 - Question one wants to answer
 - Expertise
 - Feasibility (CPU time, model complexity)
 - “Environment” (what approaches do others use)
 - “Marketing” (what kind of models “sell”)

How to build a model

- ▶ Figure out what the question/hypothesis/problem is you want to address.
- ▶ Decide what kind of model will best help you to answer your question (and if a model is useful at all)!
- ▶ Design, implement and test the model.
- ▶ Use the model to answer your question.

Stochastic Models

Limitations of deterministic models

- ▶ With deterministic models, we can not address questions such as
 - How likely/probable is an outbreak/infection to occur?
 - How likely is it that a pathogen goes extinct? (applies to both the within-host or between-host levels)
 - What variability should we expect when looking at real data?
- ▶ Any question that requires an answer in the form of a probabilistic statement needs stochastic methods.

Quick detour 1 – random numbers

- ▶ To do any kind of stochastic/probabilistic simulation, we need to produce random numbers
- ▶ But computers are deterministic machines...
- ▶ Solution: pseudo-random numbers (**reproducible!**)
 - One needs to set a seed, otherwise the computer produces RN depending on the current system time and results won't be reproducible.
- ▶ Back when: Quite a few random number generators (RNG) were bad - the numbers they produced were not “random enough”. Many a published simulation study was wrong because of bad RNG.
- ▶ Today: Almost all RNG that come with programs such as R and Matlab are very good (the numbers are “really random”). Current “favorite” RNG of most folks is the Mersenne Twister.
- ▶ R can generate RN not only from uniform distributions but all kinds of other distributions (runif, rnorm, rpois, rbinom, ...).
- ▶ We have already used RN without really discussing them. When?

Stochasticity – Observational error

▶ Observational error

- The “true” dynamics of the virus is described by V , but you can only measure/observe $O(V)$
- For instance you could sample people/animals and count virus. This might lead to observed values that are (log)normally distributed around the true value of V :
 $O=N(V,\sigma)$
- Observational error does not affect the dynamics of the system

Observational noise

$$\dot{U} = -bUV$$

True system dynamics

$$\dot{I} = bUV - \delta I$$

$$\dot{V} = pI - cV$$

$$\hat{U} = ?$$

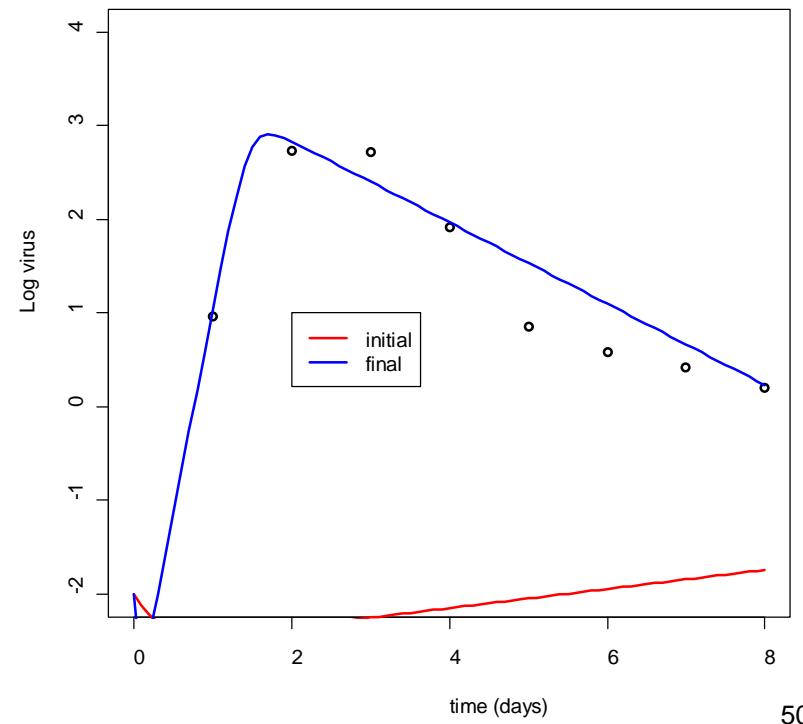
What you measure

$$\hat{I} = ?$$

$$\hat{V} = F(V)$$

Observational noise

- ▶ We assumed that only this kind of noise was present (or at least was dominant) when we did fitting.
- ▶ Specifically, we assumed that the dynamics was properly described by our ODE model, with (log)-normally distributed noise due to measurement error.
- ▶ Other assumptions about error lead to different objective functions (Maximum Likelihood).



Stochasticity – process noise

- ▶ Process noise (sometimes called process error)
 - The dynamics of the system is affected by error/noise.
 - External noise (e.g. fluctuations in weather/metabolism) can be added to the model equations.
 - Internal noise (fluctuations in parameters) can be included by sampling a parameter (e.g. infection rate) from a distribution at every time step.
 - Process error/noise propagates through the system.

Process noise

$$\dot{U} = -bUV + N$$

$$\dot{I} = bUV - \delta I + N$$

$$\dot{V} = pI - cV + N$$

$$\dot{U} = -N(b)UV$$

$$\dot{I} = N(b)UV - \delta I$$

$$\dot{V} = pI - cV$$

Stochastic differential equations (SDE)

- ▶ One type of stochastic models are stochastic differential equations (SDE).
- ▶ The math behind stochastic processes and properly implementing SDE on a computer is tricky.
- ▶ If you are interested:
 - “An algorithmic introduction to numerical simulation of stochastic differential equations”, D.J. Higham, SIAM Review, Education Section, 43, 2001 (available on his webpage at <http://fox.maths.strath.ac.uk/~aas96106/>)
 - Kloeden, P.E., Platen, E., 1992. Numerical Solution of Stochastic Differential Equations. Springer, Berlin
 - Publications by Des Higham and Kevin Burrage
- ▶ Since SDE are tricky, we will use discrete-time models to play around with noise.

Discrete stochastic model – R example

- ▶ The program SISMID-U9-noise.r runs the equations shown below twice.
- ▶ Add noise to the 2nd set of equations in any way you want (see previous slides for options).
- ▶ Check:
 - How does random number generation and (not) using a seed affect the output?
 - How do different types of noise (additive, multiplicative, etc.) affect the result?
 - How does the magnitude of noise affect the results?

$$U_{t+\tau} = U_t - (bUV)\tau$$

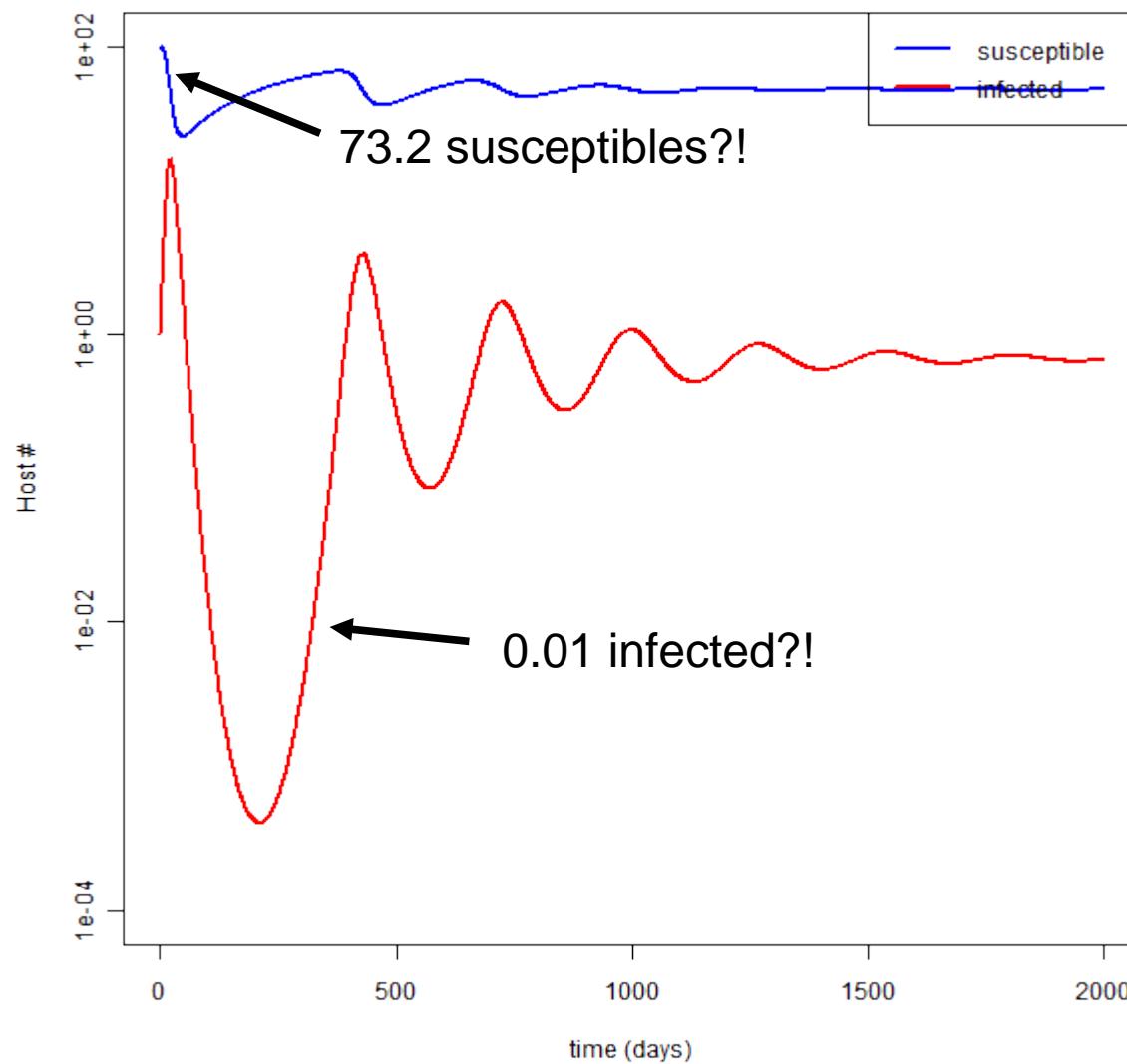
$$I_{t+\tau} = I_t + (bUV - \delta I)\tau$$

$$V_{t+\tau} = V_t + (pI - cV)\tau$$

Stochasticity so far

- ▶ Can be added to equations, easy for difference equations, trickier for differential equations.
- ▶ Computationally relatively fast.
- ▶ Very flexible, noise can be added in many ways.
- ▶ Setting noise to zero brings us back to deterministic models -> easy comparison.
- ▶ Real systems have inherent demographic stochasticity, even if there is “no noise”.

Demographic stochasticity



Demographic stochasticity

- ▶ Discrete events (e.g. birth/death) happen randomly at random times.
- ▶ This can be implemented using event-driven approaches.
- ▶ The most common used approach is called the Gillespie algorithm (sometimes also referred to as Stochastic Simulation Algorithm, SSA)
 - Gillespie introduced his method(s) in 1977
 - Not much used initially, since it requires fast computers
 - Lots of development in recent years

Event-driven model

$$\dot{U} = -bUV$$

$$\dot{I} = bUV - \delta I$$

$$\dot{V} = pI - cV$$

Transition (reaction/event)	Propensity
$U \rightarrow U - 1, I \rightarrow I + 1$	bUV
$I \rightarrow I - 1$	δI
$V \rightarrow V + 1$	pI
$V \rightarrow V - 1$	cV

The propensity (rate) multiplied with the time step gives the probability that a given event occurs

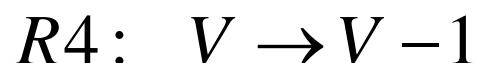
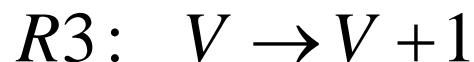
Gillespie's direct method

- ▶ Compute all propensities and the sum of all propensities, P_{tot}
- ▶ The random time at which the next event occurs is $t = -\text{Log(RND)}/P_{\text{tot}}$
- ▶ The event that occurs is randomly chosen, with probability proportional to its propensity
- ▶ Perform event, update time, return to step 1

Transition (reaction/event)	Propensity
$U \rightarrow U - 1, I \rightarrow I + 1$	bUV
$I \rightarrow I - 1$	δI
$V \rightarrow V + 1$	pI
$V \rightarrow V - 1$	cV

Event-driven model: some terminology

Reactions/Events/Transitions



State-change matrix

	$R1$	$R2$	$R3$	$R4$
--	------	------	------	------

U	-1	0	0	0
-----	----	---	---	---

I	+1	-1	0	0
-----	----	----	---	---

V	0	0	+1	-1
-----	---	---	----	----

$$\dot{U} = -bUV$$

$$\dot{I} = bUV - \delta I$$

$$\dot{V} = pI - cV$$

Gillespie's method

- ▶ The original method is very slow. As soon as numbers get large, it's not feasible anymore.
- ▶ There are several ways of speeding up computation
 - Fixed time steps. Easy/fast for computer, but approximation. We need to make sure that only few events occur during the time step. Done by pretty much all Agent-based models.
 - Smart approximations to Gillespie algorithm. Can potentially speed up code by a lot.
 - Switch to Fortran or C (painful).

Evolutionary dynamics

Modeling evolution

- ▶ During evolution, new phenotypes/genotypes usually occur at low frequency initially.
- ▶ Often we are interested in probabilities of fixation/extinction.
- ▶ This requires a stochastic approach.
- ▶ We can apply the previously discussed approaches to some simple evolutionary dynamics questions.

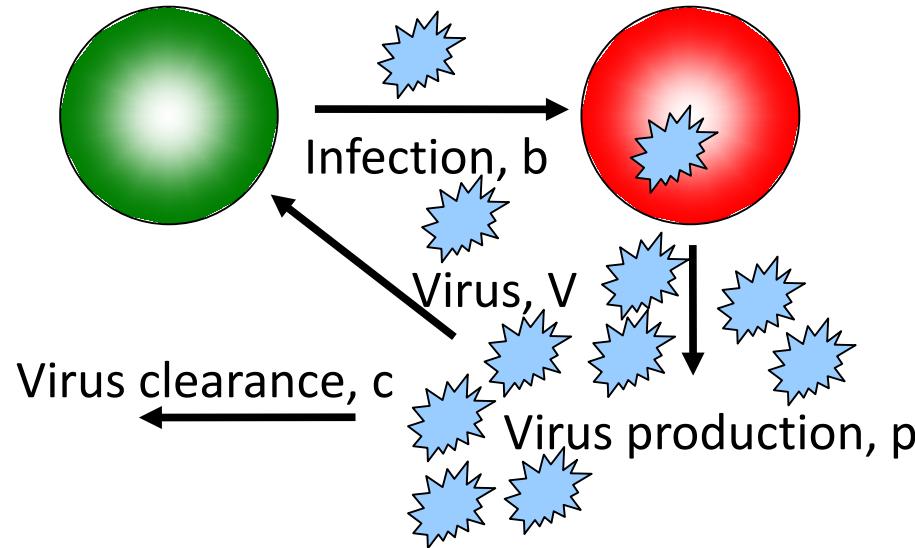
A “real” example: emergence of drug resistance

- ▶ Consider an acute virus infection (influenza).
- ▶ The host/patient receives drug treatment.
- ▶ There is a chance that during the infection a resistant mutant is generated.
- ▶ Resistance generation is an unlikely event, initially the resistant mutant starts with low numbers (1).
- ▶ Stochastic models are needed/appropriate.
- ▶ This is basically “within-host evolution”.

2-strain model for influenza infection

Uninfected cell, U

Infected cell, I



$$\dot{U} = -bUV_s \quad (\text{uninfected cells})$$

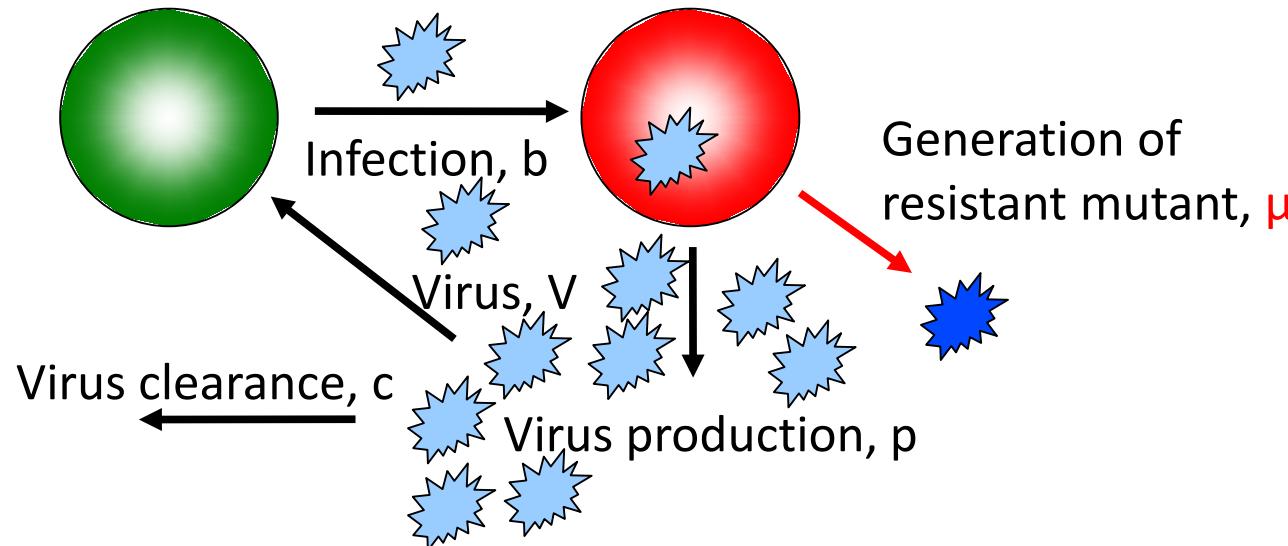
$$\dot{I}_s = bUV_s - \delta I_s \quad (\text{drug sensitive infected cells})$$

$$\dot{V}_s = pI_s - cV_s \quad (\text{drug sensitive virus})$$

2-strain model for influenza infection

Uninfected cell, U

Infected cell, I



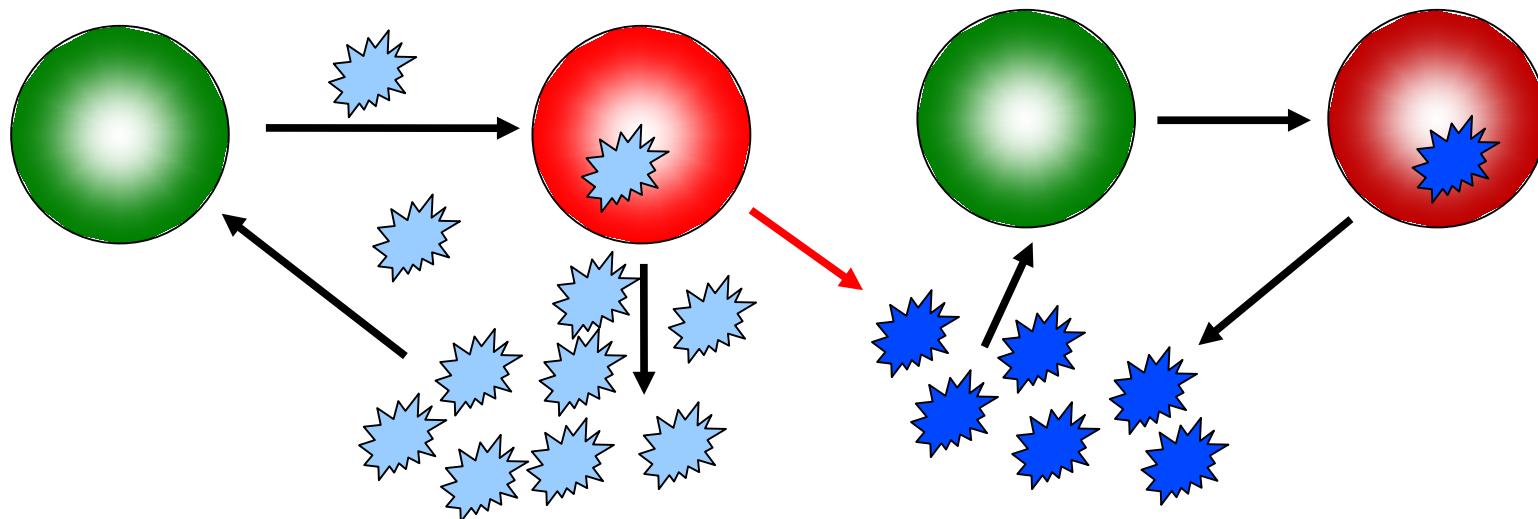
$$\dot{U} = -bUV_s \quad (\text{uninfected cells})$$

$$\dot{I}_s = bUV_s - \delta I_s \quad (\text{drug sensitive infected cells})$$

$$\dot{V}_s = (1 - \mu)pI_s - cV_s \quad (\text{drug sensitive virus})$$

$$\dot{V}_r = \mu pI_s \quad (\text{drug resistant virus})$$

2-strain model for influenza infection



$$\dot{U} = -bUV_s - bUV_r \quad (\text{uninfected cells})$$

$$\dot{I}_s = bUV_s - \delta I_s \quad (\text{sensitive infected cells})$$

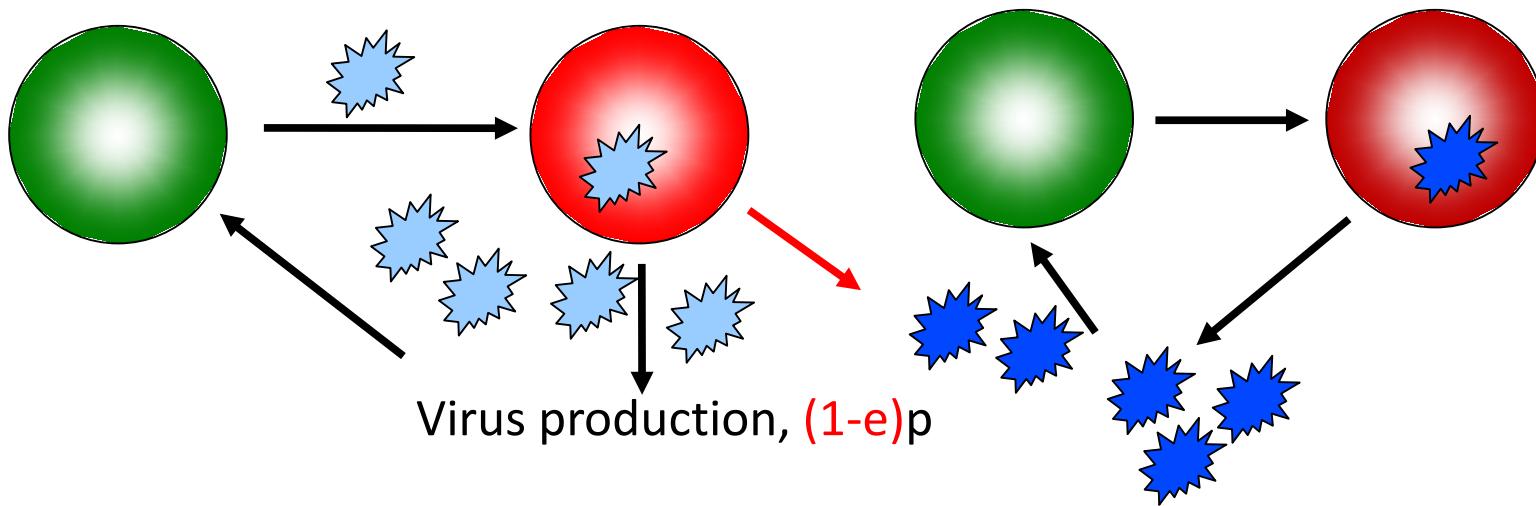
$$\dot{I}_r = bUV_r - \delta I_r \quad (\text{resistant infected cells})$$

$$\dot{V}_s = (1-\mu)pI_s - cV_s \quad (\text{sensitive virus})$$

$$\dot{V}_r = \mu pI_s + (1-f)pI_r - cV_r \quad (\text{resistant virus})$$

Fitness cost

Including antiviral drug treatment



$$\dot{U} = -bUV_s - bUV_r \quad (\text{uninfected cells})$$

$$\dot{I}_s = bUV_s - \delta I_s \quad (\text{sensitive infected cells})$$

$$\dot{I}_r = bUV_r - \delta I_r \quad (\text{resistant infected cells})$$

$$\dot{V}_s = (1-e)(1-\mu)pI_s - cV_s \quad (\text{sensitive virus})$$

$$\dot{V}_r = (1-e)\mu pI_s + (1-f)pI_r - cV_r \quad (\text{resistant virus})$$

Drug resistance for influenza

- ▶ Let's try to answer a "real" question: "How does the probability that resistance emerges depend on a given level of treatment?"
- ▶ How would we go about answering this?

$$\dot{U} = -bUV_s - bUV_r$$

$$\dot{I}_s = bUV_s - \delta I_s$$

$$\dot{I}_r = bUV_r - \delta I_r$$

$$\dot{V}_s = (1-e)(1-\mu)pI_s - cV_s$$

$$\dot{V}_r = (1-e)\mu pI_s + (1-f)pI_r - cV_r$$

Drug resistance for influenza

- ▶ Let's try to answer a "real" question: "How does the probability that resistance emerges depend on a given level of treatment?"
- ▶ How would we go about answering this?
 - 1. Set e to some value.
 - 2. Run the stochastic simulation N times.
 - 3. Record for how many of those N simulations the resistant strain emerged (we need to define this).
 - 4. Change e .
 - 5. Go back to step 2 until we have done the simulation for a number of e values (e.g. between 0 and 1 in steps of 0.1).
 - 6. Plot result: e on the x-axis, fraction of simulations for which we had resistance emergence on y-axis.

$$\dot{U} = -bUV_s - bUV_r$$

$$\dot{I}_s = bUV_s - \delta I_s$$

$$\dot{I}_r = bUV_r - \delta I_r$$

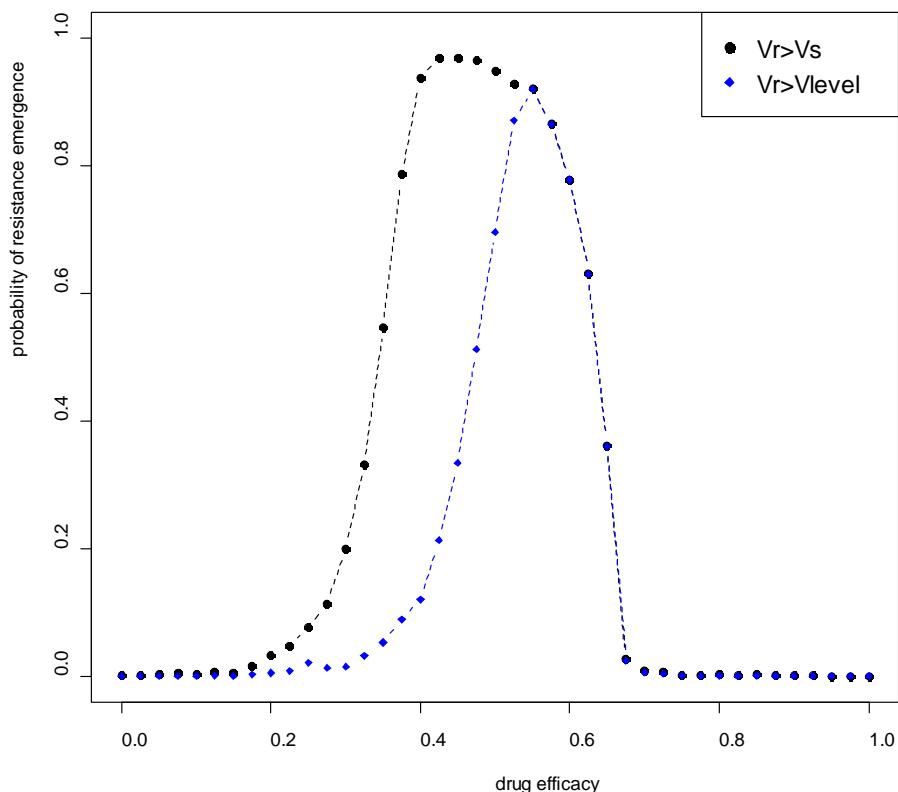
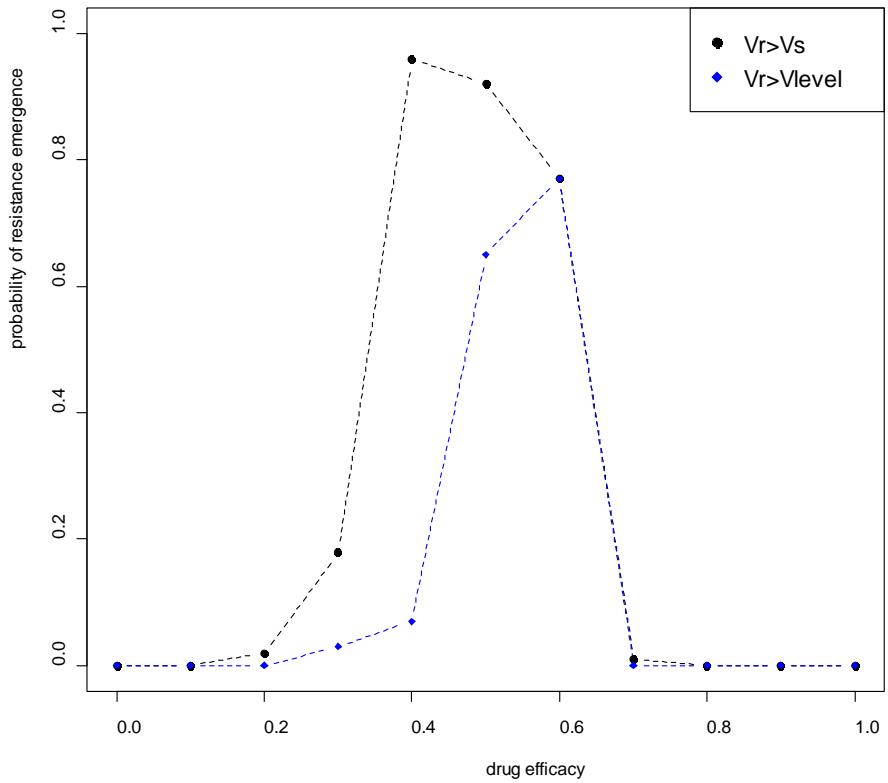
$$\dot{V}_s = (1-e)(1-\mu)pI_s - cV_s$$

$$\dot{V}_r = (1-e)\mu pI_s + (1-f)pI_r - cV_r$$

Drug resistance for influenza - R

- ▶ The “pure” Gillespie method is too slow for this project, even with unrealistically low numbers for cells/virus.
- ▶ A smart approximate method exists in the **adaptivetau** package in R.
- ▶ Install **adaptivetau** if you haven’t already.
- ▶ Open SISMID-U9-evolution.r. Read & understand the code.
- ▶ Run the model, make sure you understand the results.

Drug resistance for influenza - R



Stochasticity - Discussion

- ▶ Noise/randomness enters in many ways: Observation error, internal/external fluctuations, demographic stochasticity.
- ▶ Stochasticity can be implemented in models in different ways. It always makes the model somewhat more difficult and slower to run.
- ▶ If you have a question for which you think ODEs are a good approximation, start with those.
- ▶ If you have a system or question where stochasticity is important, you need to use some kind of stochastic approach (SDE, discrete model with noise, purely stochastic (Gillespie), Agent-based model...)

Stochastic models and data

- ▶ One can fit data to stochastic models.
- ▶ Most work so far has been done on the population/between-host/epidemiology level under the label of infectious disease inference.
- ▶ It's complicated, definitely beyond this module. If you want to learn more:
 - "Design and Analysis of Vaccine Studies" by Halloran, Longini and Struchiner (2009), Springer – currently most comprehensive book on the topic
 - "Analysis of Infectious Disease Data" by Niels Becker (1989) – good theory, somewhat outdated with regard to computational aspects
 - "Bayesian Analysis for Emerging Infectious Diseases" by Jewell et al. (2009) Bayesian Analysis
 - "Inference in Epidemic Models without Likelihoods" by McKinley et al. (2009) International Journal of Biostatistics
 - Some of the other SISMID modules

Further reading

- ▶ Bolker (2008) “Ecological Models and Data in R” (covers some fitting of stochastic models to data)
- ▶ Keeling and Rohani (2008) “Modeling Infectious Diseases”, chapter 6
- ▶ Gillespie algorithm: Gillespie (1977) Journal of Physical Chemistry
- ▶ GillespieSSA package: Pineda-Krch (2008) Journal of Statistical Software
- ▶ Some people/groups who work on state-of-the art stochastic/hybrid solvers: Linda Petzold, Daniel Gillespie, Yang Cao, Kevin Burrage, Yiannis Kaznessis,...

Models with memory

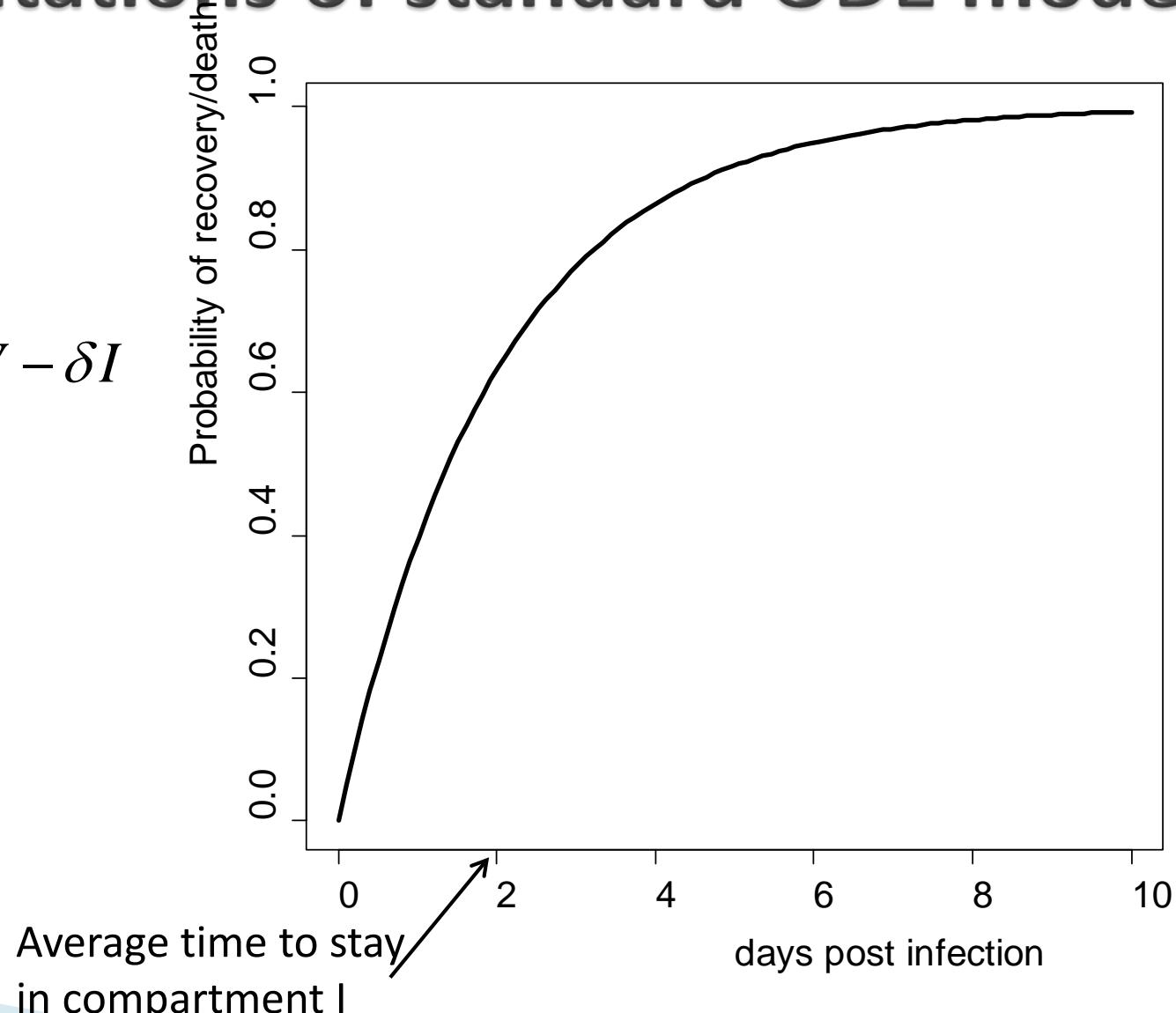
Limitations of standard ODE models

- ▶ Simple ODE models are “memory-less”, the dynamics of the system only depends on the **current** state of the system.
- ▶ Example: For the simple within-host model we have looked at, infected cells die at a constant rate, δ . A cell that was infected 10 seconds has the same chance of dying as a cell that was infected 10 hours ago.

$$\dot{I} = bUV - \delta I$$

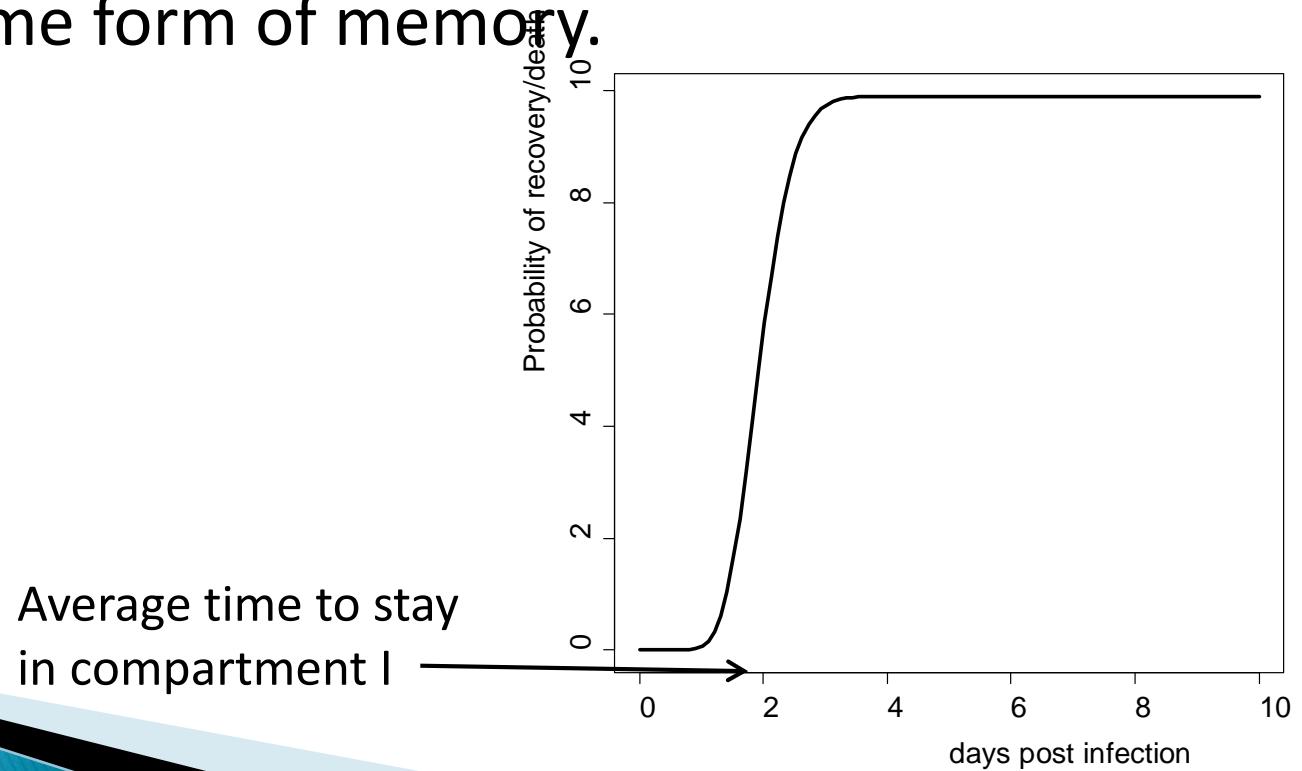
Limitations of standard ODE models

$$\dot{I} = bUV - \delta I$$



Realistic transitions

- ▶ It is more likely that an infected cell dies after a certain time, with some variation.
- ▶ To take this into account, we need to keep track of the time/age since infection, i.e. our model needs to include some form of memory.



Tracking age - PDEs

- One way to explicitly specify an age since infection in the model leads to a partial differential equation (PDE)

$$\frac{\partial I(t, \tau)}{\partial t} = -\delta(\tau)I(t, \tau) - \frac{\partial I(t, \tau)}{\partial \tau}$$

Death rate depends on age since infection Age since infection “aging” of infecteds

$$\frac{dI(t)}{dt} = -\delta I(t)$$

Comments on PDEs

- ▶ Mathematically “elegant”, some analytics is often possible but more challenging than ODEs.
- ▶ More difficult to implement numerically. Only rudimentary support in R, e.g. solvers in deSolve package.
- ▶ There is another, simpler way to fix the problem with the infected cell life-span, based on introducing additional equations which represent dummy compartments.

Dummy compartments for a realistic life-span

$$\dot{U} = \lambda - dU - bUV$$

$$\dot{I}_1 = bUV - n\delta I_1$$

$$\dot{I}_2 = n\delta I_1 - n\delta I_2$$

$$\dot{I}_3 = n\delta I_2 - n\delta I_3$$

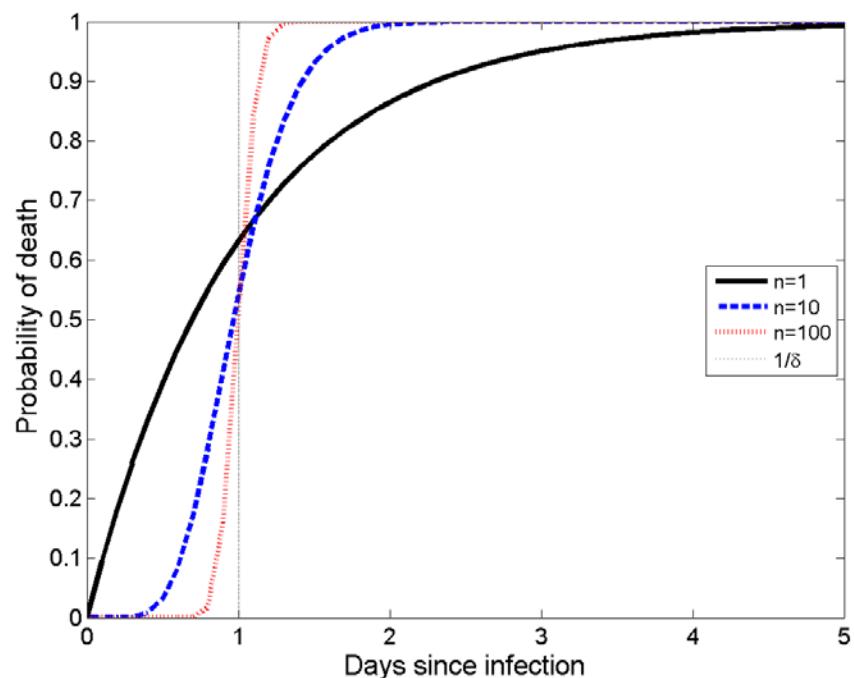
⋮

$$\dot{I}_n = n\delta I_{n-1} - n\delta I_n$$

$$\dot{V} = \sum_{i=1}^n p_i I_i - cV$$

Lloyd (2001a,b) Proc Soc B

n dummy compartments. Infected cells spend $1/n\delta$ in each compartment, with a total mean duration of $n/n\delta=1/\delta$, as before. For $n=1$, we have the previous model. As n gets larger, the lifespan becomes more concentrated around the mean value.



Delay Differential equations (DDE)

- ▶ Sometimes it is useful to consider time lags.
 - Example: Production of new virions starts some time after a cell has become newly infected.
- ▶ Now the dynamics of the system depends on the **current and past** state of the system. Again, ODE's can't do that because they are "memory-less". To keep track of past states, one needs delay differential equations (DDE).

$$\dot{U} = \lambda - dU - bUV$$

$$\dot{I} = bUV - \delta I$$

$$\dot{V} = pI(t-\tau) - cV$$

Production of virus
proportional to
number of infected
cells time τ ago.

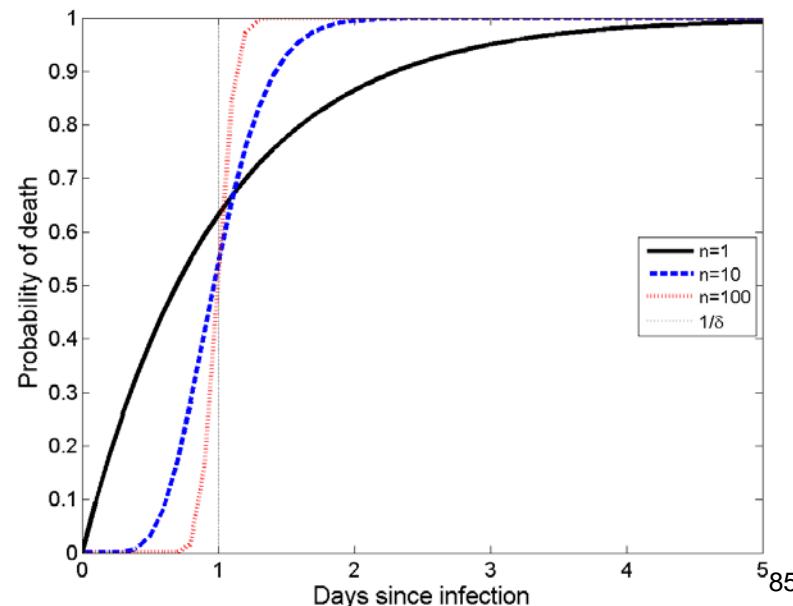
Using DDEs

- ▶ The most tedious way is to write your own DDE solver.
- ▶ A better way is to use an existing solver, for instance `dede()` in `deSolve` or the package `PBSddesolve`.
- ▶ Another option is to rewrite DDE using dummy compartments. This is the same trick as the one I mentioned for PDEs. It is sometimes called the “linear chain trick”.

Linear Chain trick for delays

- ▶ Only the last compartment produces virus.
- ▶ Since it takes a newly infected cell $n/ng=1/g$ amount of time before it reaches the last compartment, we have implemented a delay between cells becoming infected and starting to produce virus.
- ▶ Similar to having a latent compartment with non-exponential transitions (see dummy compartment example above).

$$\begin{aligned}\dot{U} &= \lambda - dU - bUV \\ \dot{I}_1 &= bUV - ngI_1 \\ \dot{I}_2 &= ngI_1 - ngI_2 \\ \dot{I}_3 &= ngI_2 - ngI_3 \\ &\vdots \\ \dot{I}_f &= ngI_{n-1} - \delta I_f \\ \dot{V} &= p\mathbf{I}_f - cV\end{aligned}$$



Models with memory – R example

- ▶ Open SISMID-U9-memory.r
- ▶ Try to understand the code. The situation/model is again the simple within-host virus model. The model is run twice, once with a DDE using the built-in DDE solver (dede) from the deSolve package, once with dummy compartments.
- ▶ Run the model & see how different delays and dummy compartments affect the results.

$$\dot{U} = \lambda - dU - bUV$$

$$\dot{I}_1 = bUV - ngI_1$$

$$\dot{V} = p\mathbf{I}(t - \tau) - cV$$

$$\dot{I}_2 = ngI_1 - ngI_2$$

:

$$\dot{I}_f = ngI_{n-1} - \delta I_f$$

$$\dot{V} = p\mathbf{I}_f - cV$$

Comments on memory models

- ▶ The simple memory-less ODE model is unrealistic, however, sometimes it's a decent approximation.
- ▶ The more realistic models don't change steady states, but can change the dynamics.
- ▶ If used for data fitting, the simple model and the more realistic model can produce different results, for instance lead to different estimates for R_0 .
- ▶ Further reading: *Alun Lloyd (2001a,b) Proc Soc B, Helen Wearing et al. (2005) PLoS Medicine*

Spatially explicit Models

So far – homogenous models

- ▶ Different entities, such as virus/cells or uninfected/infected hosts, were assumed to be well mixed and bump into each other randomly (mass-action) and “live” in a homogenous space.
- ▶ As we saw, mass-action was not ideal (recall the HIV example) but fixing some problems with mass-action by using saturating functions still assumed essentially homogeneous mixing.
- ▶ If we want to consider spatial structure, we need to use spatially explicit models.

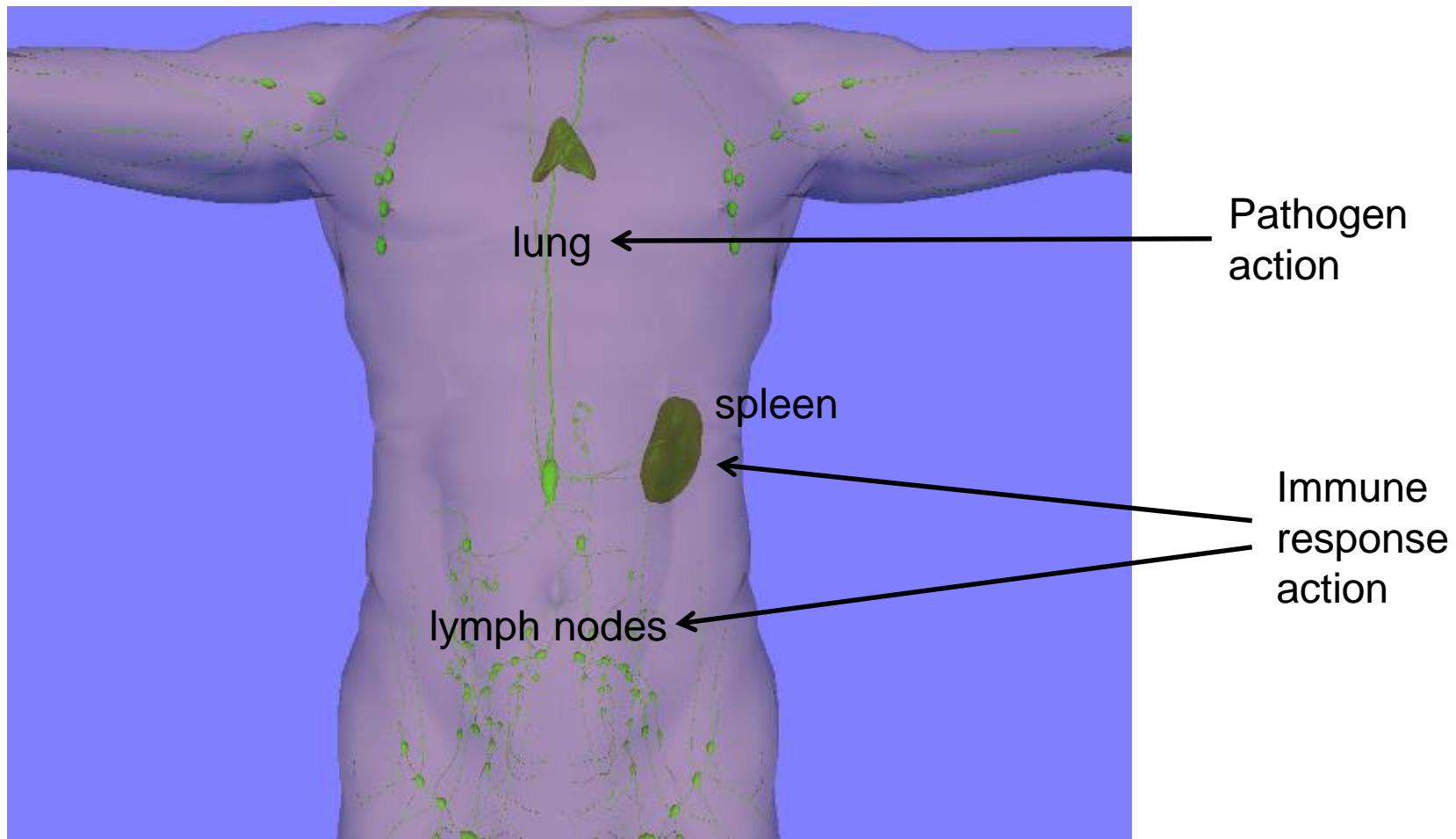
Spatial Models

- ▶ Metapopulation/patch models
 - Use ODEs or discrete time/stochastic compartmental models to simulate dynamics of populations in different distinct sites.
 - Migration/interaction terms couple the equations/sites.
 - Simple and straightforward extension of non-spatial compartmental models.
 - Still non-spatial within a given site.
- ▶ Partial differential equations
 - Space is an explicit dimension of the model.
 - One can sometimes do some analytics (but it's not easy).
 - For certain situations realistic enough.
 - Potentially difficult to implement on a computer.
- ▶ Agent-based (individual-based) models
 - These models can be the most detailed/realistic.
 - Almost no analytics is possible, purely computational.
 - Needs sufficient computational resources, especially for large populations.

Metapopulation models

- ▶ On each patch/site, a dynamical process occurs.
Sites/populations are coupled to form a metapopulation.
- ▶ Entities can move between sites
- ▶ Entities from different sites can interact

Modeling multiple “locations”



Modeling multiple “locations”

$$\dot{U} = -bUV_l$$

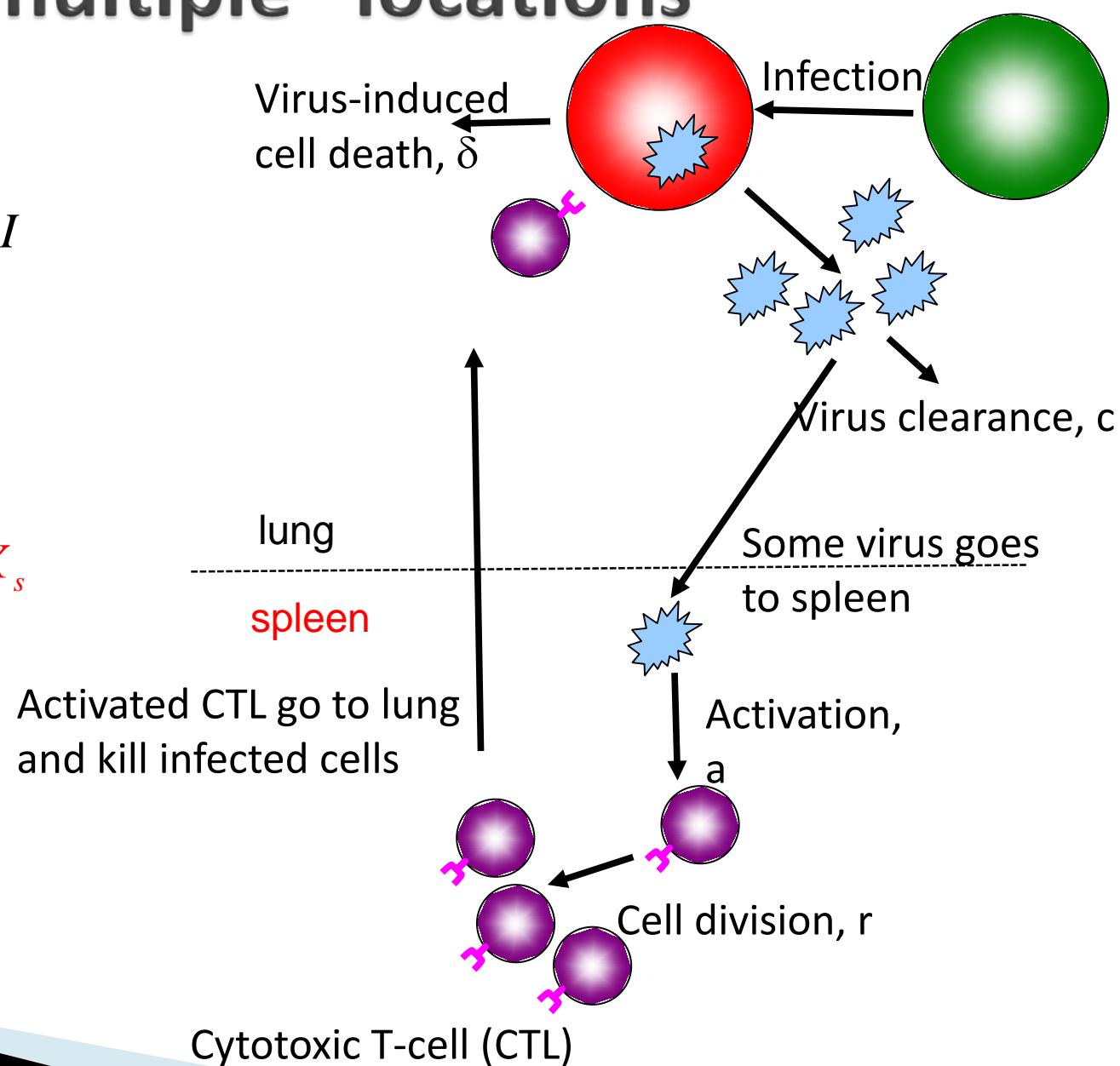
$$\dot{I} = bUV_l - \delta I - kX_l I$$

$$\dot{V}_l = pI - c_l V_l - mV_l$$

$$\dot{X}_l = fX_s - dX_l$$

$$\dot{V}_s = mV_l - c_s V_s$$

$$\dot{X}_s = aV_s + rX_s - fX_s$$



Agent-based Models

Agent-based models (ABM)

- ▶ For ABM, every individual/agent is modeled explicitly.
- ▶ ABM are very flexible, they can be very detailed and realistic.
- ▶ One can usually not write down equations, ABM are almost purely computational.
- ▶ Since ABM are complex, they have the usual drawbacks (many parameters, many unknowns).
- ▶ To run ABM on a computer usually requires lots of CPU power.

Writing ABM

- ▶ In principle, any programming language can be used.
- ▶ If speed is crucial, use Fortran/C (but the programming can be **very** tedious).
- ▶ R, Matlab and similar languages make programming somewhat easier, but the code is still much more involved compared to simple compartmental models.
- ▶ Specialized ABM languages exist: NetLogo, Swarm, Repast, MASON,...

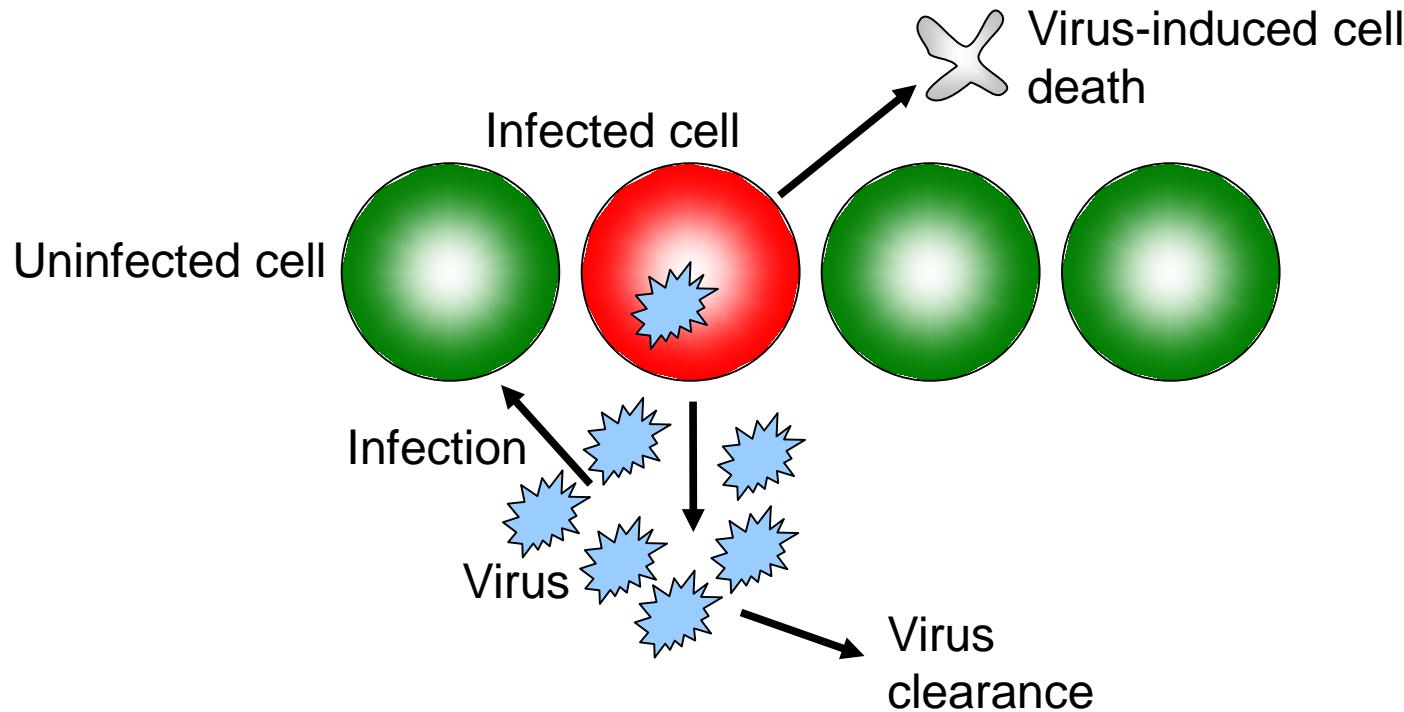
NetLogo

- ▶ Based on the Logo programming language
- ▶ Mainly meant as teaching tool
- ▶ Very user-friendly, easy to program
- ▶ Free! (<http://ccl.northwestern.edu/netlogo/>)
- ▶ Powerful enough to do some science/research with it
- ▶ Many model examples
- ▶ Models are mostly stochastic, but can be deterministic.
Time step is **fixed** – not event-driven like Gillespie algorithm (ABM with Gillespie are usually way too CPU intensive).

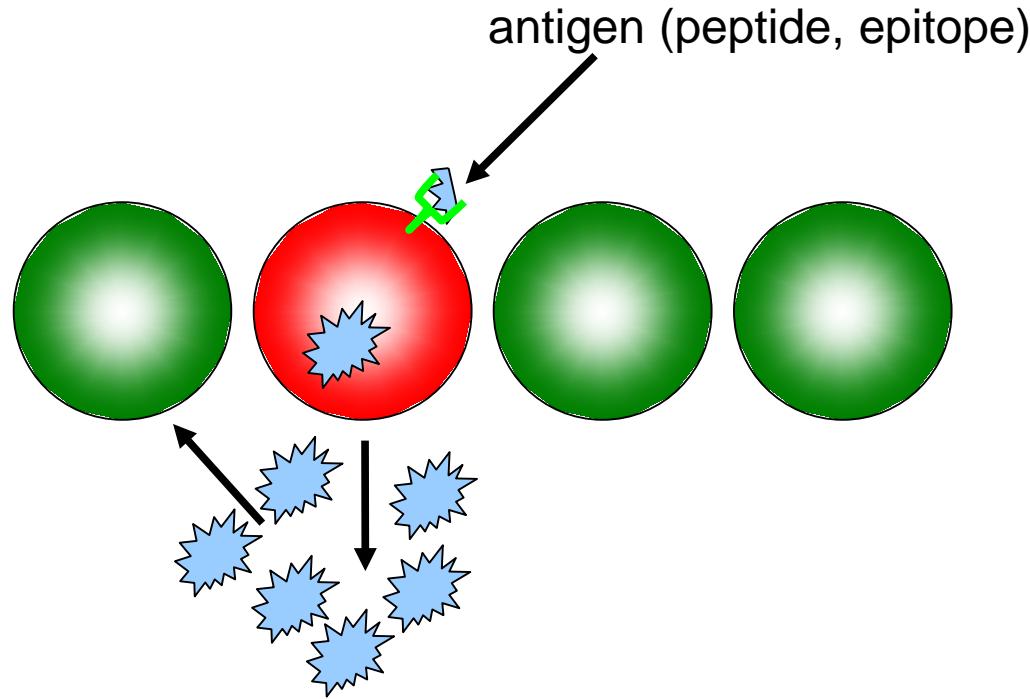
NetLogo and research – an example

- ▶ Based on: “Sharing the burden: Antigen transport and firebreaks in immune responses” A. Handel, A. Yates, SS. Pilyugin, R. Antia (2009), Journal of the Royal Society Interface

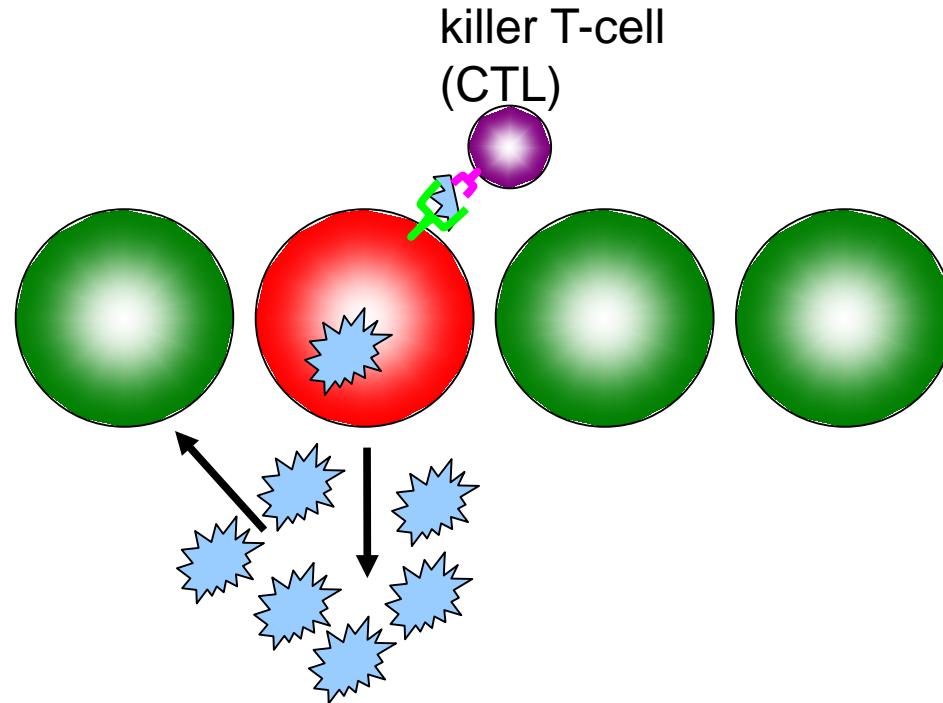
A virology/immunology primer



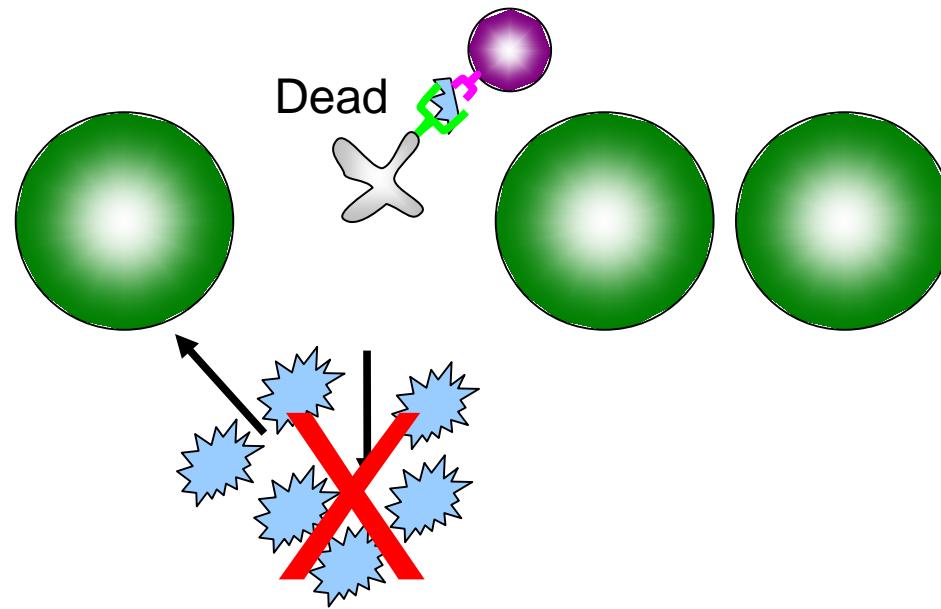
A virology/immunology primer



A virology/immunology primer

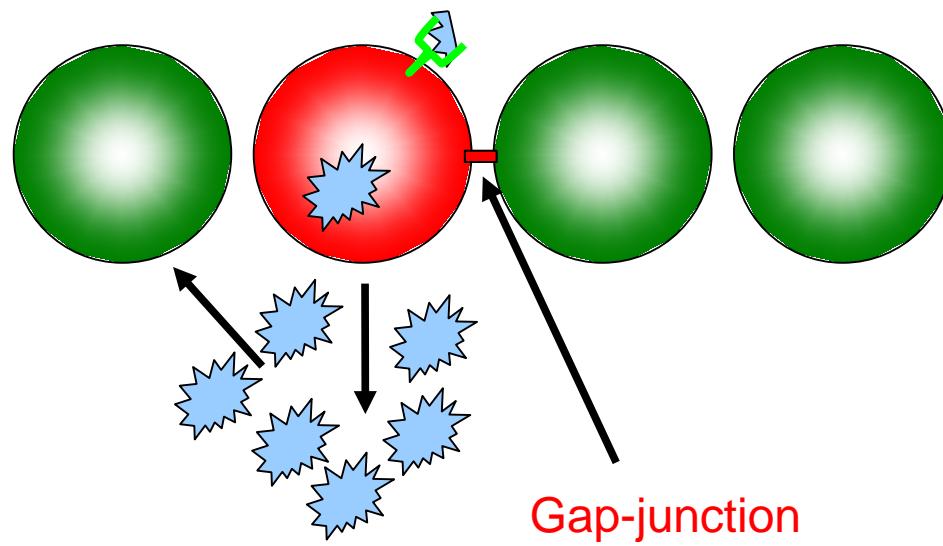


A virology/immunology primer

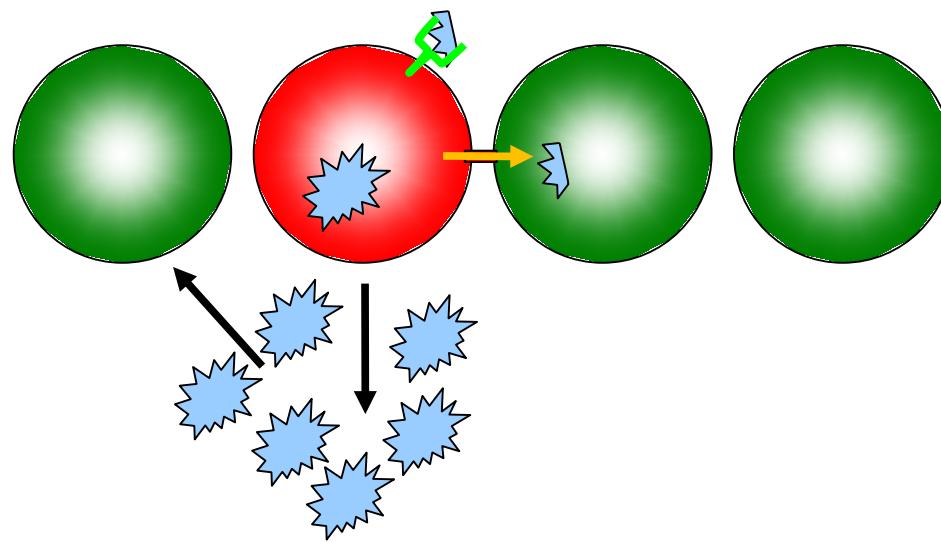


The good: Virus production interrupted
The bad: A dead cell (immunopathology)

Gap-junctions during viral infection

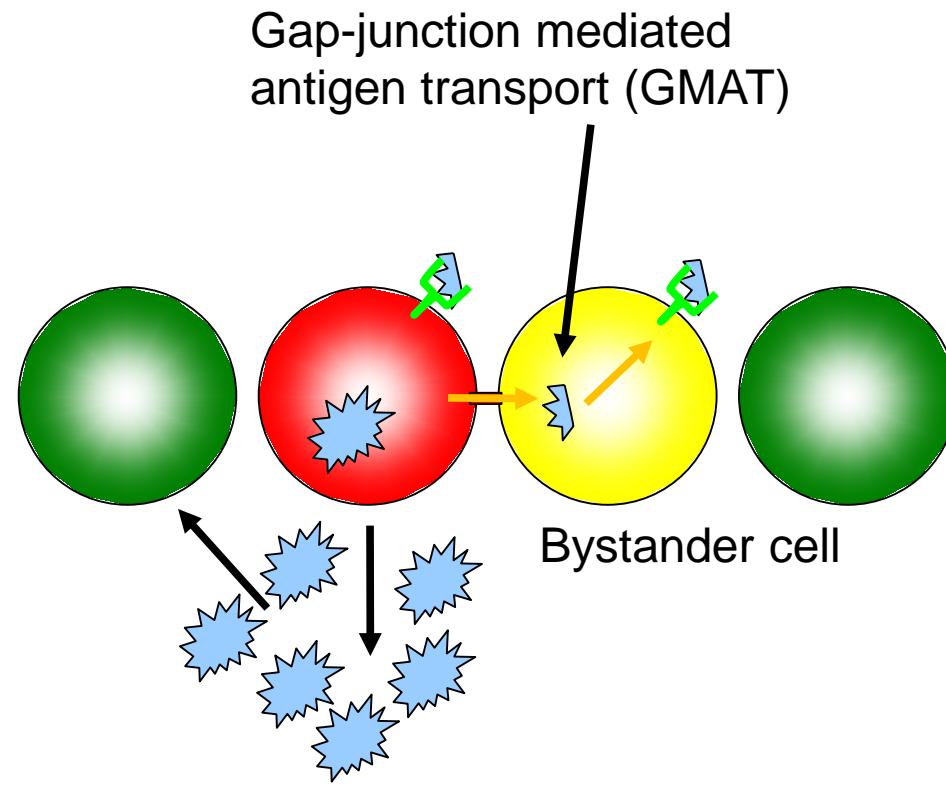


Gap-junctions during viral infection



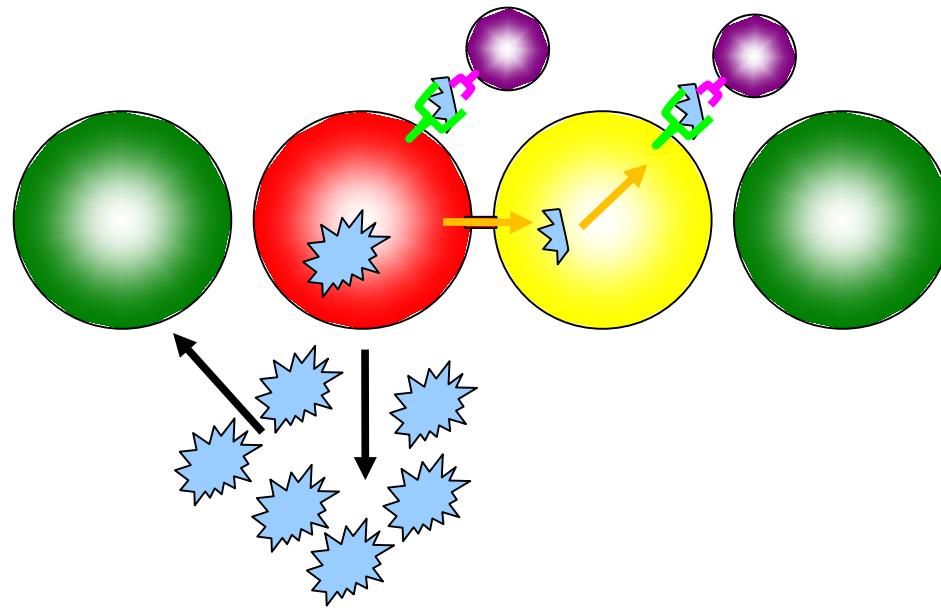
Neijssen et al. (2005) Nature

Gap-junctions during viral infection

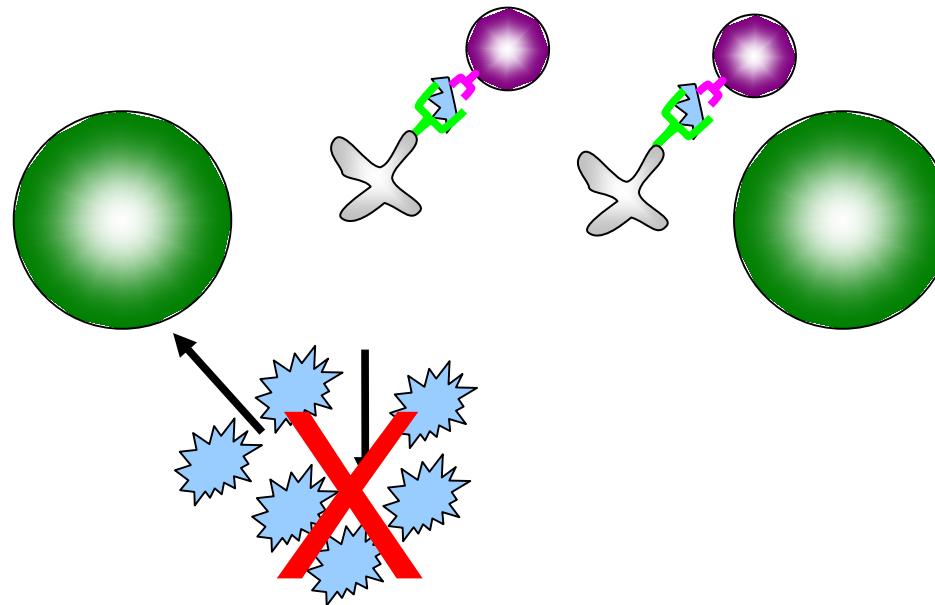


Neijssen et al. (2005) Nature

Gap-junctions during viral infection



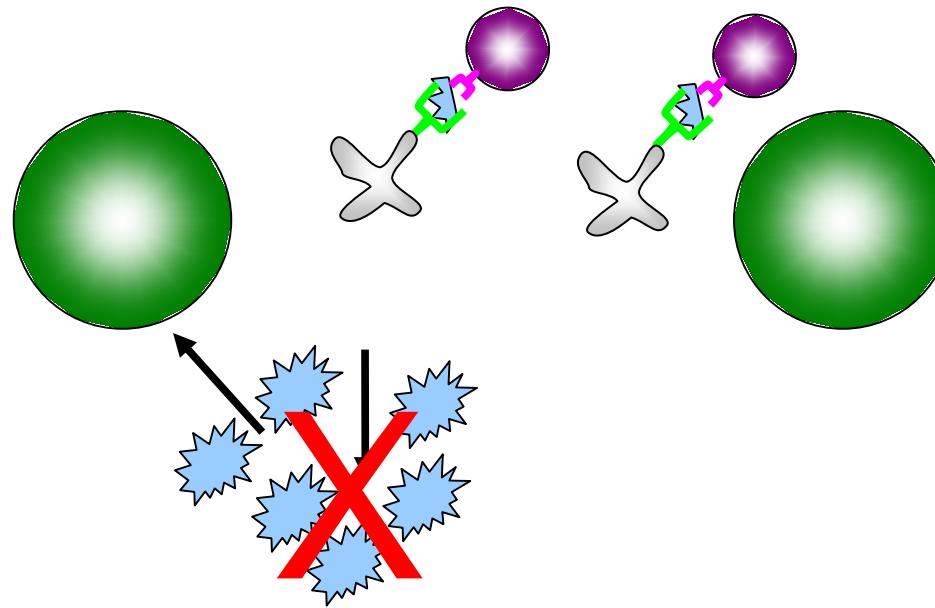
Gap-junctions during viral infection



The good: Virus production interrupted before it even started

The bad: 1) More dead cells.
2) CTL that are busy killing bystander cells can't kill infected cells

Gap-junctions during viral infection



Question: Are gap-junctions potentially useful for the host?

A mathematical model of the system

$$\dot{U} = -bUV - \textcolor{red}{g}UI \quad (\text{uninfected cells})$$

$$\dot{I} = bUV + bBV - dI - kXI \quad (\text{infected cells})$$

$$\dot{B} = \textcolor{red}{g}UI - bBV - kXB \quad (\text{bystander cells})$$

$$\dot{C}_I = kXI - \delta C_I \quad (\text{CTL - infected cell complex})$$

$$\dot{C}_B = kXB - \delta C_B \quad (\text{CTL - bystander cell complex})$$

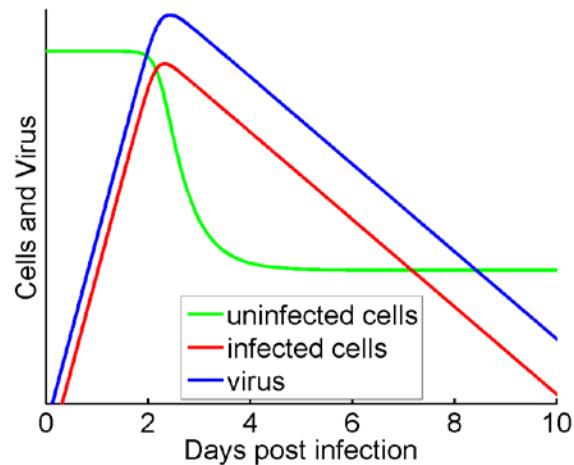
$$\dot{V} = p(I + C_I) - cV \quad (\text{free virus})$$

$$\dot{T} = rT \quad (\text{total CTL})$$

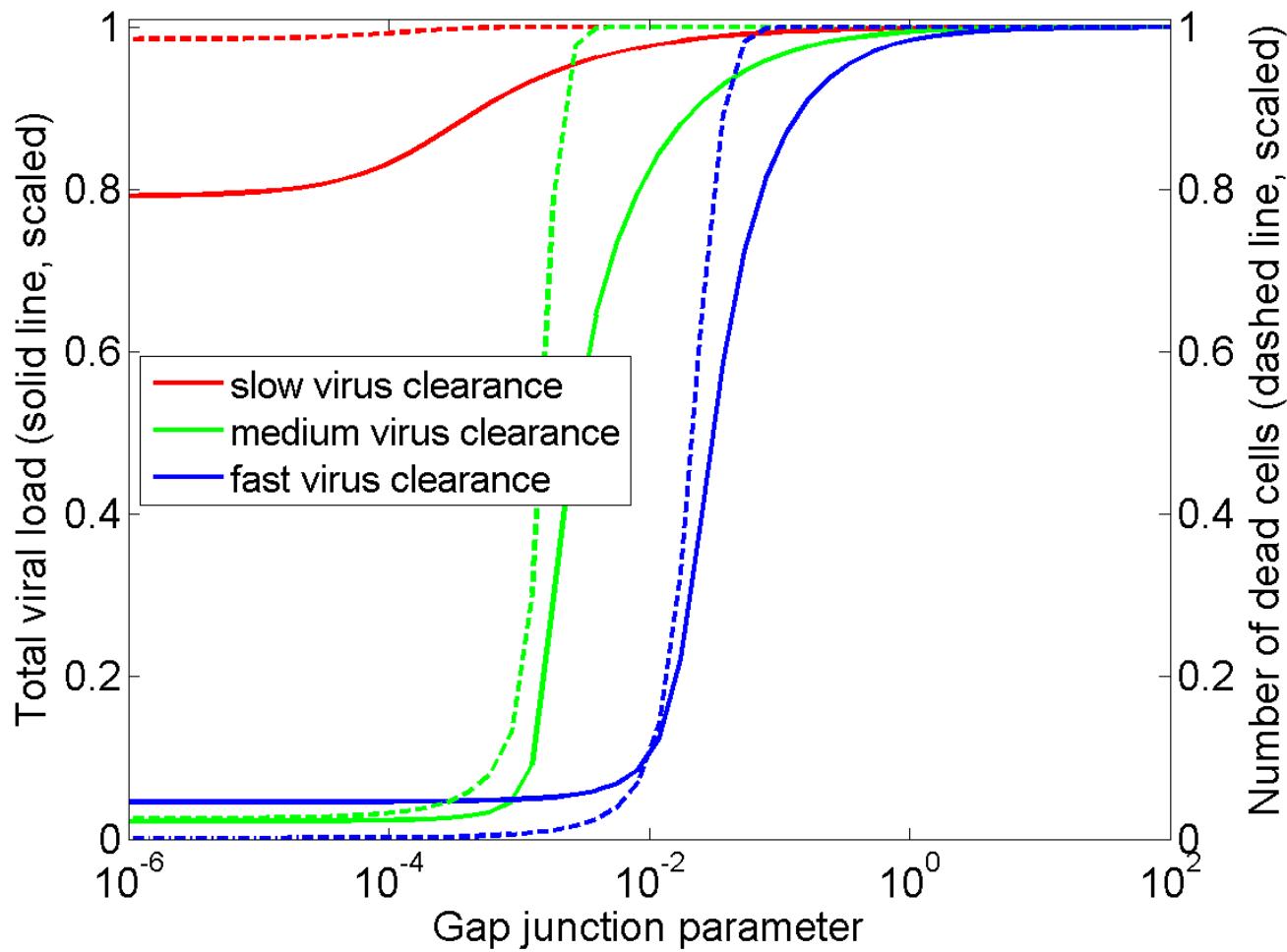
$$X = T - C_I - C_B \quad (\text{free CTL})$$

Analysis

- ▶ Run the model/simulation
- ▶ Record total virus load (area under curve) and total number of dead cells
- ▶ Do that for different values of the gap-junction parameter g



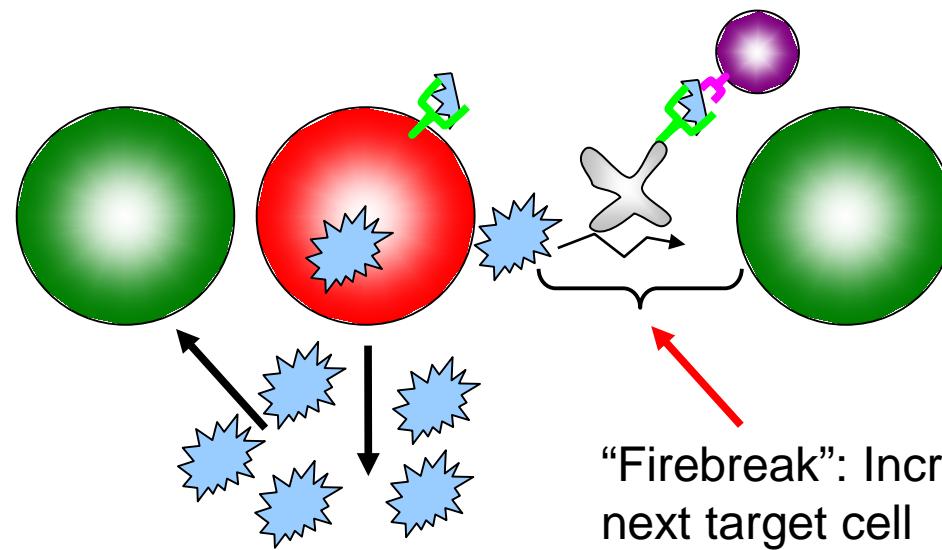
Results



So far, so bad

- ▶ The model suggests that virus load and immunopathology increase with increased gap junction-mediated antigen transport (GMAT).
- ▶ BUT: We have not yet considered spatial effects.

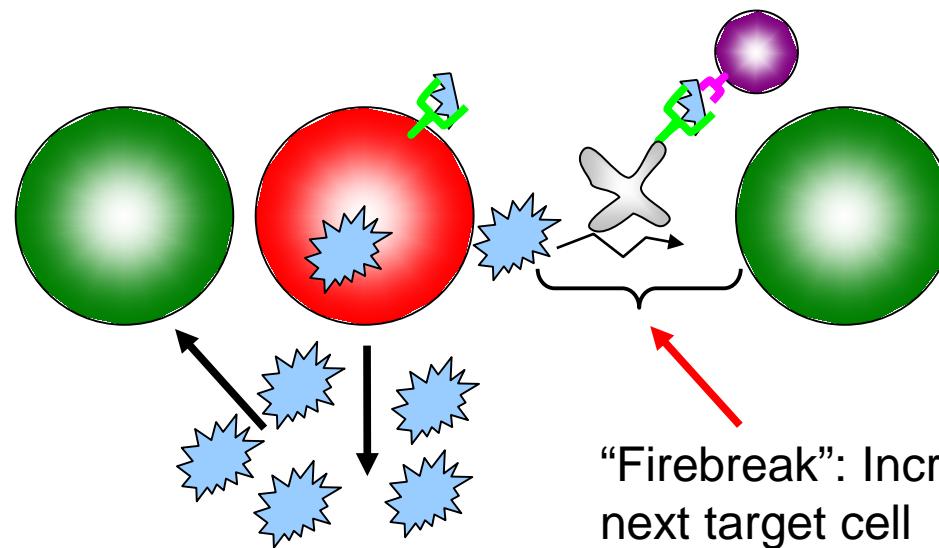
Gap-junctions as firebreaks



“Firebreak”: Increased distance to next target cell

Gap-junctions as firebreaks

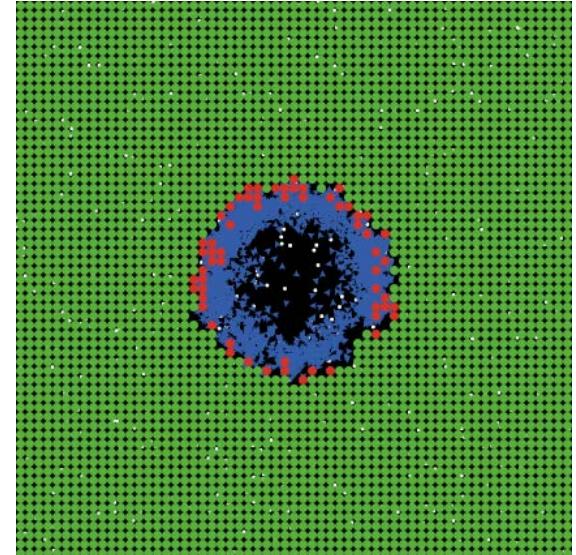
- ▶ To study firebreaks, an ODE model does not work well. We need a model that includes space.



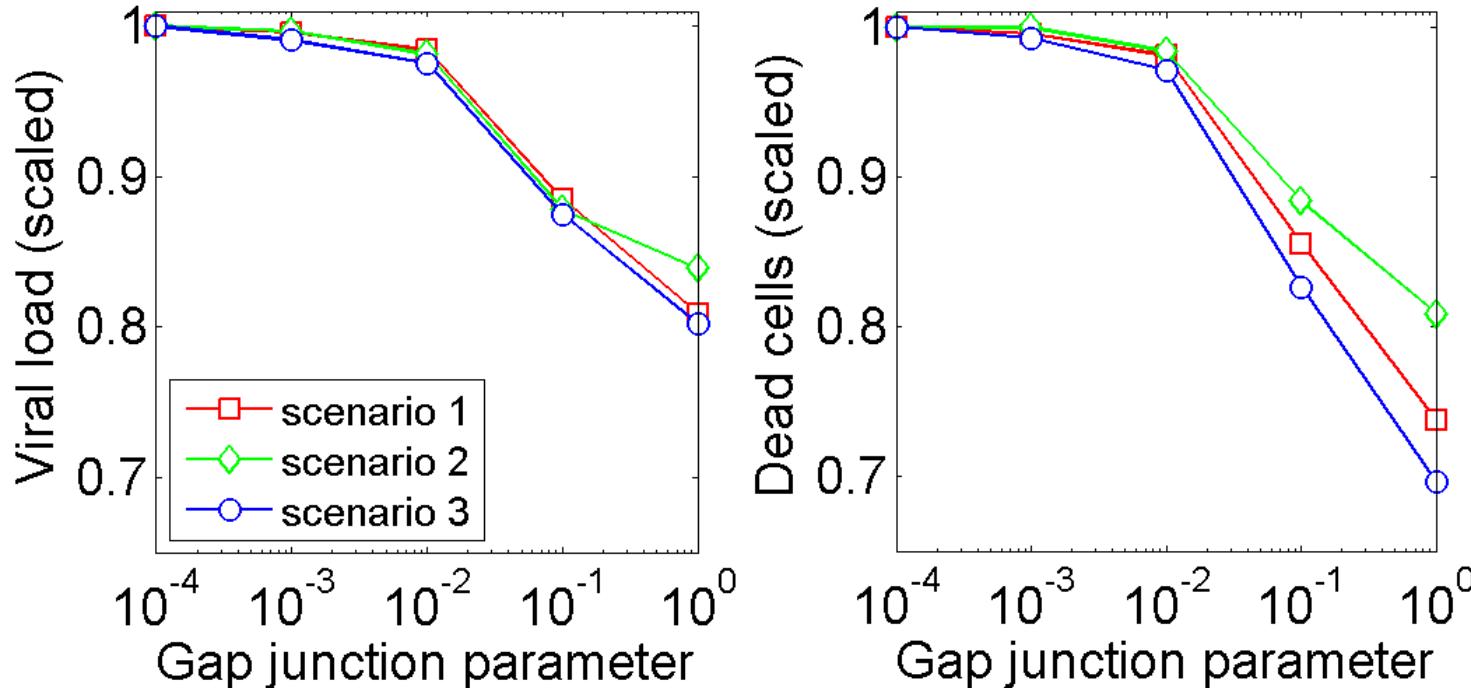
“Firebreak”: Increased distance to next target cell

An agent-based model for gap-junctions

- ▶ The players
 - Virus, Target (epithelial) cells, CTL
- ▶ The place
 - A square grid filled with (fixed) target cells, representing a patch of epithelial tissue
- ▶ The action
 - Infection starts at middle of grid
 - Virions diffuse around; are cleared at a fixed rate; bind to and enter cells and thereby infect uninfected cells
 - Uninfected cells become infected, produce virus, die
 - CTL slowly enter the “scene”, move around, can find and kill infected cells
 - Infected cells produce bystander cells, which can be killed by CTL



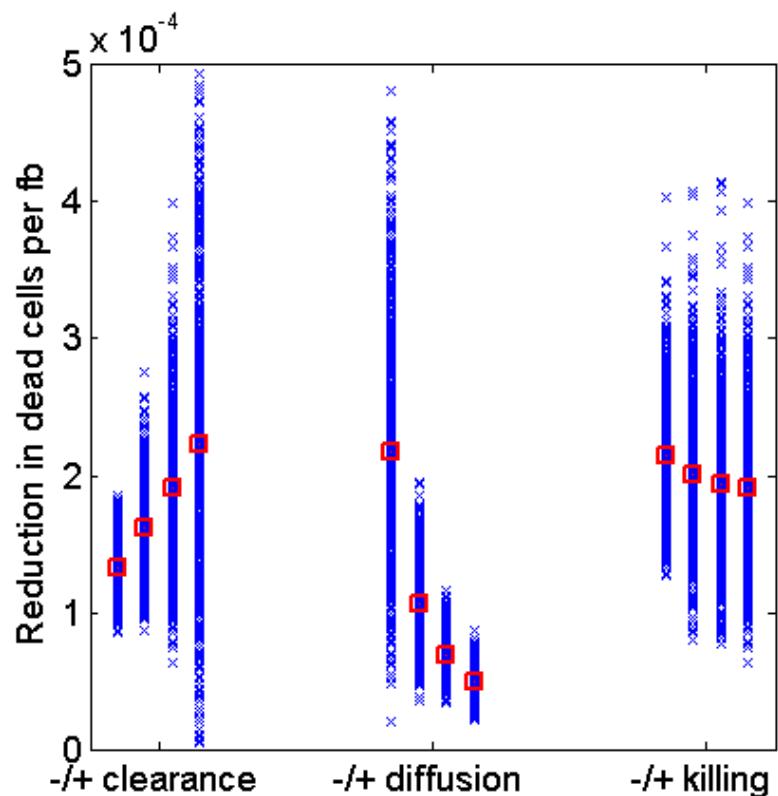
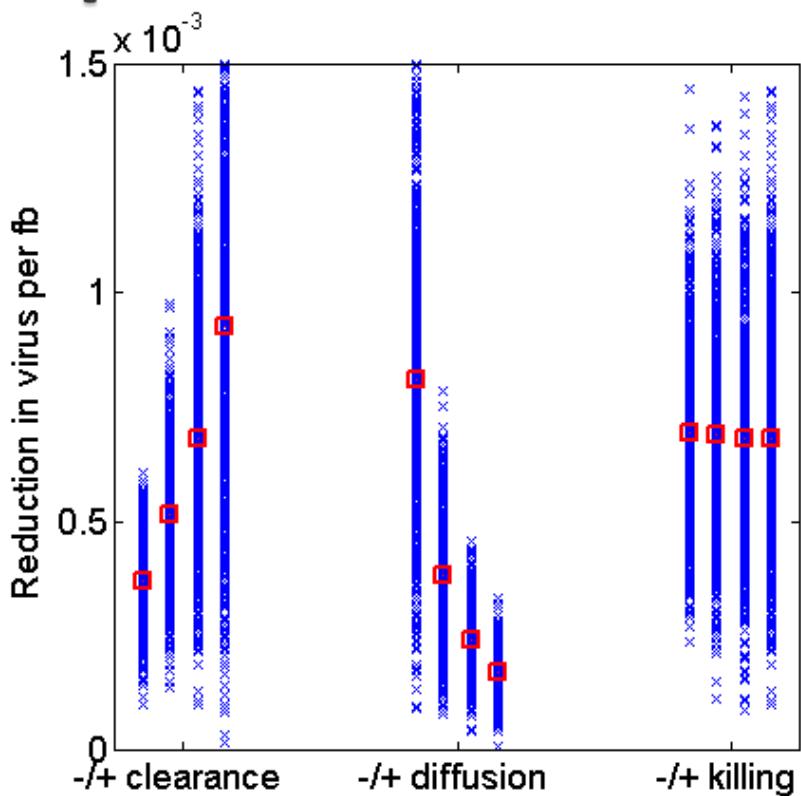
Spatial results



Shown are averages of 200 simulations.

The 3 different scenarios have different values for parameters such as diffusion speed of virions and CTL, probability of virus death and killing of infected/bystander cells by CTL per time-step, etc.

Spatial results



GMAT/ the firebreak has a greater effect if virus clearance is fast and diffusion slow. Speed of CTL killing has little effect.

A firebreak (FB) is a bystander cell killed by CTL.

Spatial results

- ▶ The spatial model suggests that GMAT might be a beneficial mechanism for the host immune response to reduce both virus load and immunopathology.
- ▶ The non-spatial differential equation model could not capture this result. → It is important to choose the right modeling framework for the question at hand.

Discussion of ABM

- ▶ ABM are the most detailed (and potentially realistic) we have seen so far, they allow one to address questions that can't be addressed with simple compartmental models.
- ▶ Model needs to be carefully tailored to the question and data.
- ▶ More complexity means less general/conceptual insights, more reliance on simulations. Almost no math/analytics is possible.
- ▶ Many parameters, usually more than in ODE models. Becomes a problem if these parameters are unknown or poorly known.
- ▶ Potentially more accurate.
- ▶ Speed can become a serious issue.
- ▶ The models are often stochastic, but don't have to be.
- ▶ Data fitting becomes hard.

Further reading – ABM

- ▶ Durrett (1999) SIAM Reviews (mathematical review of spatial model approaches)
- ▶ Grimm and Railsback (2005) “Individual-based Modeling and Ecology” Princeton U Press (focus on ecology, but approaches can also apply to within-host modeling)
- ▶ Railsback et al. (2006) Simulation (reviews several common software packages)
- ▶ Chavali et al. (2008) Trends in Immunology (review of ABM in immunology)
- ▶ Keeling and Rohani (2008) “Modeling Infectious Diseases” Princeton U. Press (mostly between-host, only a bit of spatial, but good advice)
- ▶ Bauer et al. (2009) Information Science “Agent-based modeling of host–pathogen systems: The successes and challenges”

On your own – Exploring NetLogo

- ▶ Start Netlogo
- ▶ In “Files -> Models Library” under “Biology” open the model called “Virus”
- ▶ Press “Setup”, then “Go”
- ▶ You might have to adjust the simulation speed with the speed slider
- ▶ Change around the other sliders and see how that affects the dynamics
- ▶ Pressing “Go” again stops simulation, then you can restart with “Setup/Go”
- ▶ Go to the “Information” tab to learn more about the simulation
- ▶ Go to the “Procedures” tab to see the actual code
- ▶ Explore the many more interesting models in the models library.

Summary

- ▶ Mechanistic, dynamical models are well suited for studying the dynamics of infectious diseases.
- ▶ Different types of models exist, the model choice should be driven by the question/system.
- ▶ Models always make simplifying assumptions. The applicability of the models and the conclusions drawn are only valid if the approximations made for the model are fulfilled.
- ▶ This is never the case, but often the error we make in translating (and thereby simplifying) a complex biological process to a mathematical model is small enough to make even simple models useful.
- ▶ Models are always wrong but sometimes surprisingly useful. (Also applies to all experimental model systems).

Summary

- ▶ There are many approaches to building a model
- ▶ For a given approach, there are many variants of implementing specific mechanisms (recall HIV models)
- ▶ Ideal approach:
 - Choose the model that is most suitable for the question you try to answer.
 - If you can, maybe try a few model variants.
- ▶ In reality: Model selection is based on a mix of
 - Question one wants to answer
 - Expertise
 - Feasibility (CPU time, model complexity)
 - Time to graduation/end of grant/tenure review
 - “Environment” (what approaches do others use)
 - “Marketing” (what kind of models “sell”)