Exploring the Role of Behavior in Infectious Disease Dynamics:

Mathematical Insights from World of Warcraft and other Virtual Worlds

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Disclaimer: All game images shown are taken from Blizzard's WoW website

First: What does an infectious disease epidemiologist do?

Analyzes:

- Disease risks to populations
- Origin of existing outbreaks
- Which public health strategies will help prevent outbreaks
- Which intervention strategies will end already existing outbreaks
- When to make public announcements about a health emergency

Practical epidemiologists can be like detectives:

They track down the spread of a disease by asking the infected people where they'd been, who they'd seen, etc.

This is can be incredibly difficult, but when done well, can head off the spread of infectious disease

- requires LOTS of time
- (hopefully) only a few people sick
- requires cooperation of the sick people and their families

Mathematical Epidemiologists do something a little different:

We use math to predict what disease outbreaks will look like if/when they happen

How does this work?

There are a few different methods

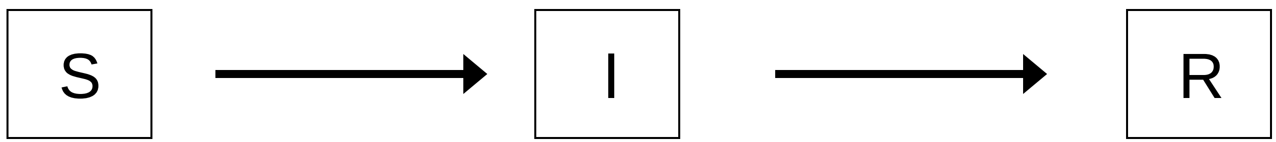
- Compartmental Models
- Network Models
- Agent Based Models (can be based on other types, but does it differently)

What are these mathematical models?

Luckily, we can represent them using pictures

Compartmental Models: a basic overview

First we group people by health status:



Compartmental Models: a basic overview

First we group people by health status:

$$S \xrightarrow{\beta} I \longrightarrow R$$

Then we consider rates of moving from one compartment into another

- Based on probabilities
  - exposure and infection from exposure : β

Compartmental Models: a basic overview

First we group people by health status:

$$\boxed{S} \xrightarrow{\beta} \boxed{I} \xrightarrow{\gamma} \boxed{R}$$

Then we consider rates of moving from one compartment into another

- Based on probabilities
  - exposure and infection from exposure : β
  - duration of illness and probability of recovery : γ

This picture tells a mathematical story

$$\boxed{S} \xrightarrow{\quad\beta\quad} \boxed{I} \xrightarrow{\quad\gamma\quad} \boxed{R}$$

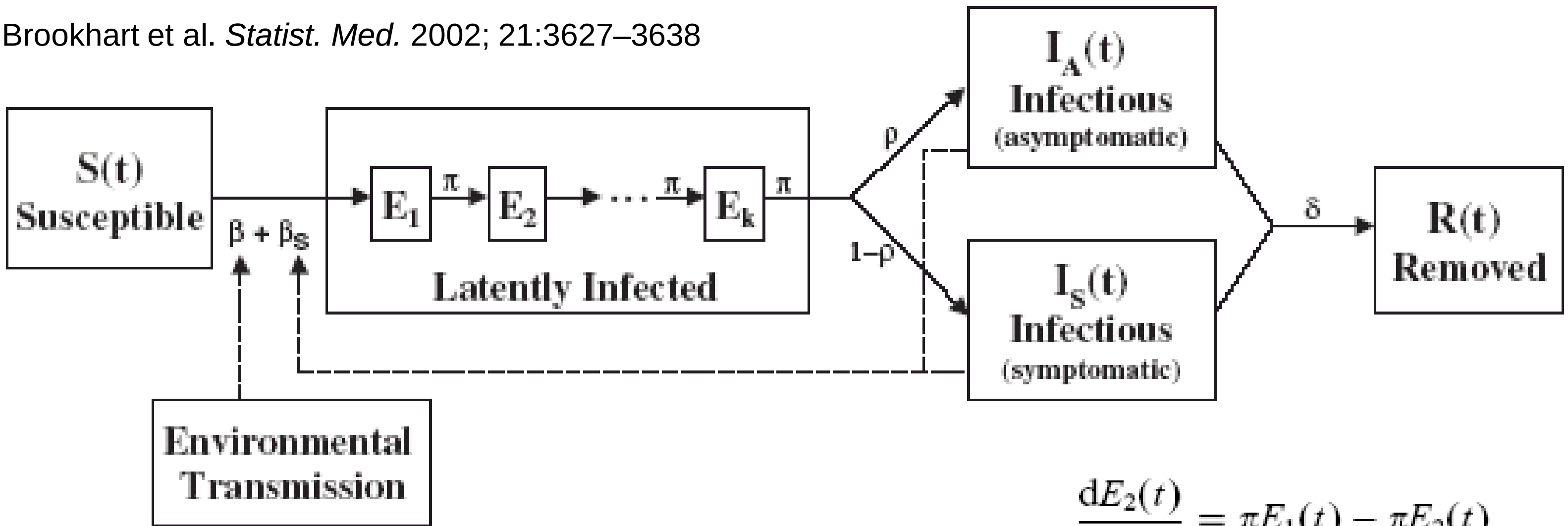
$$\frac{dS}{dt} = -\beta IS$$

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

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

The mathematics can get still more complicated

Brookhart et al. *Statist. Med.* 2002; 21:3627–3638



$$\frac{dE_2(t)}{dt} = \pi E_1(t) - \pi E_2(t)$$

$$\cdots$$

$$\frac{dE_k(t)}{dt} = \pi E_{k-1}(t) - \pi E_k(t)$$

$$\frac{dI_A(t)}{dt} = \rho\pi E_k(t) - \delta I_A(t)$$

$$\frac{dI_S(t)}{dt} = (1-\rho)\pi E_k(t) - \delta I_S(t)$$

$$\frac{dR(t)}{dt} = \delta(I_A(t) + I_S(t))$$

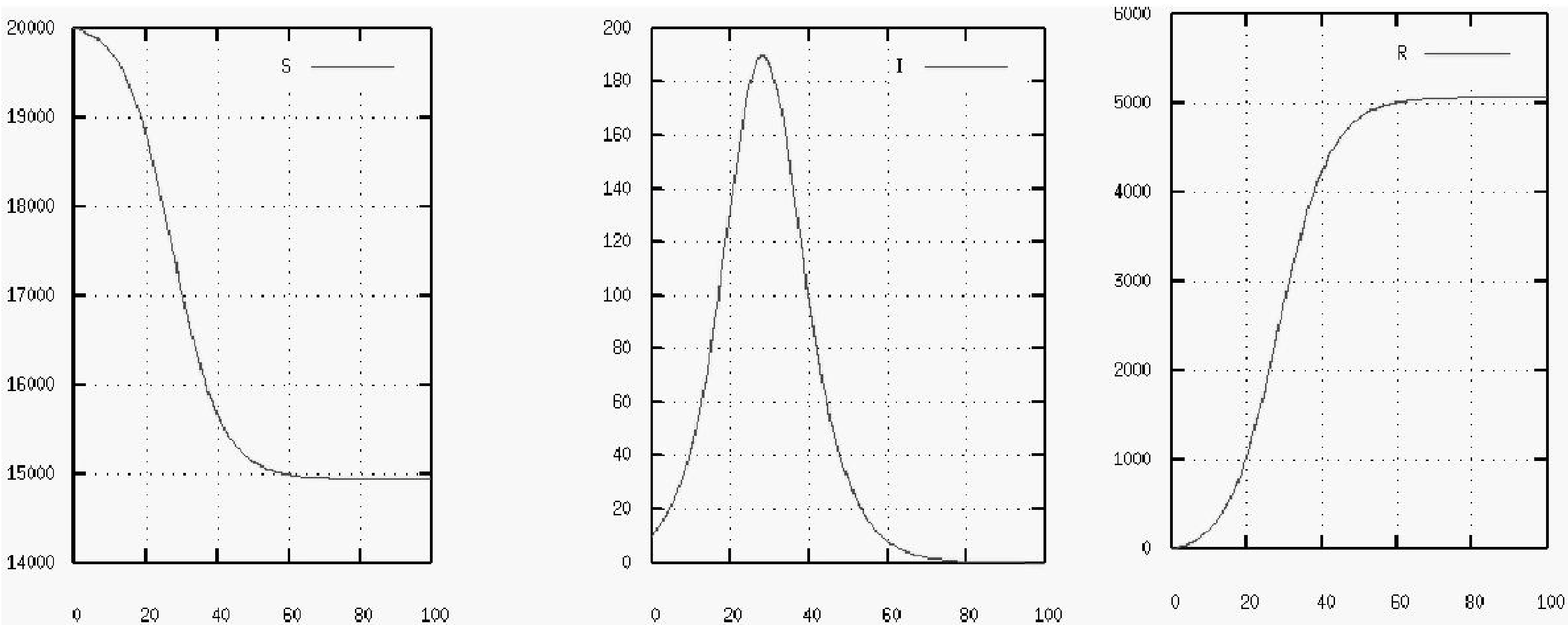
$$\frac{dS(t)}{dt} = -\beta(t)S(t) - \beta_S S(t)(I_A(t) + I_S(t))$$

$$\frac{dE_1(t)}{dt} = \beta(t)S(t) + \beta_S S(t)(I_A(t) + I_S(t)) - \pi E_1(t)$$

$$\beta(t) = I\{t \leqslant 23\}\beta_0 + I\{23 < t \leqslant 38\}\beta_1 + I\{t > 38\}\beta_2$$

These compartmental models produce nice, easily understood curves

S I R



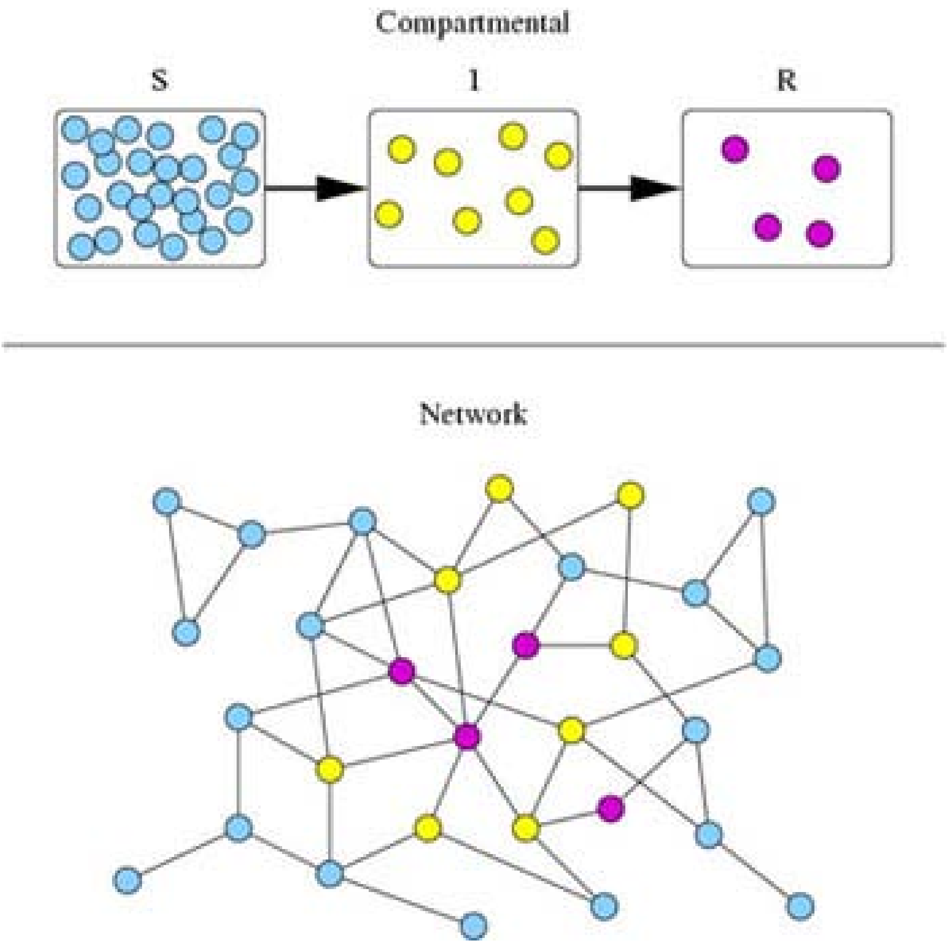
But compartmental models are not always very accurate

$$\boxed{S} \xrightarrow{\beta} \boxed{I} \xrightarrow{\gamma} \boxed{R}$$

Main reason: Assumed homogeneous, random mixing

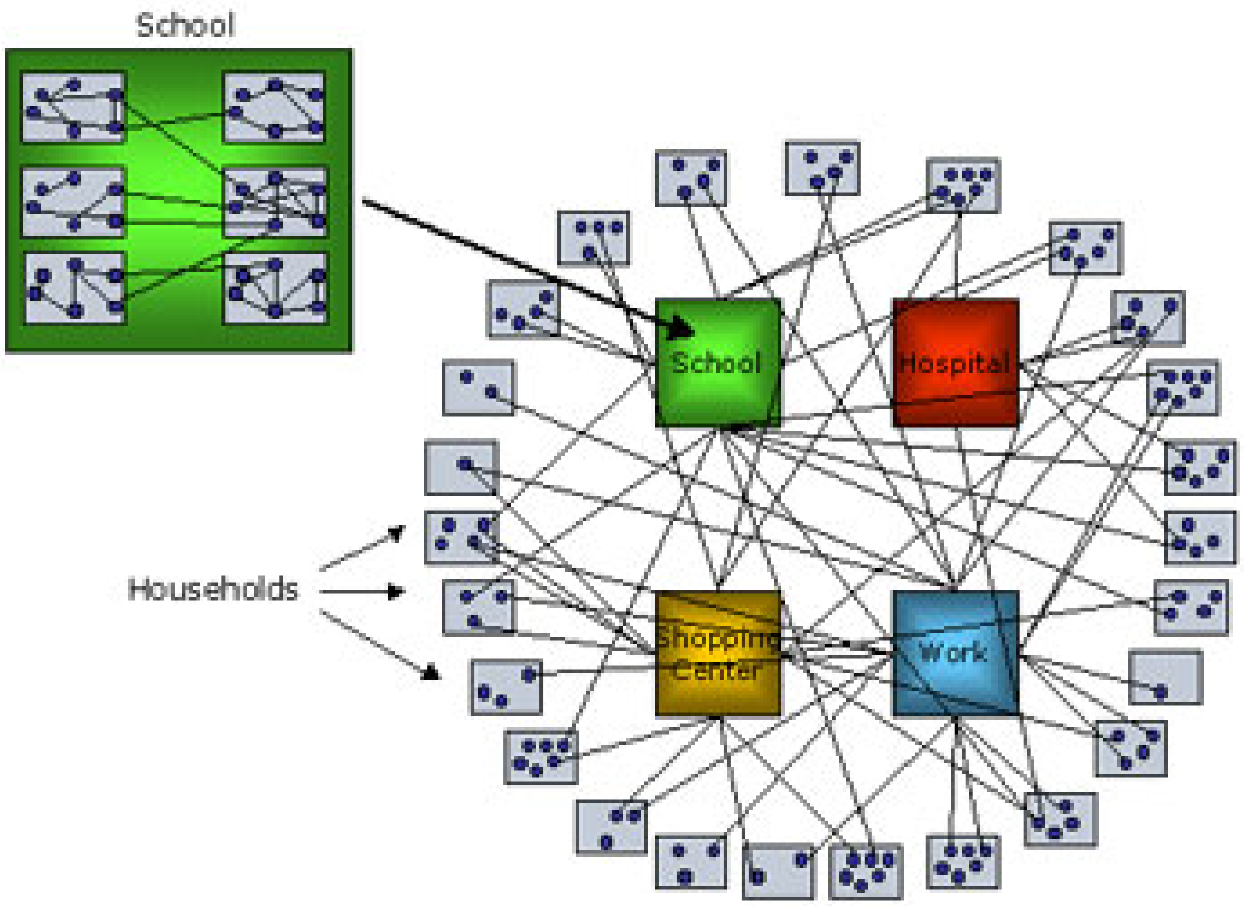
- Everyone in S has the same chance of moving into I based on assumed same chance of contacting someone from I

This leads us to Network Models:



Taken from <http://www.esi.utexas.edu/features/Archive/2003/meyers.html>

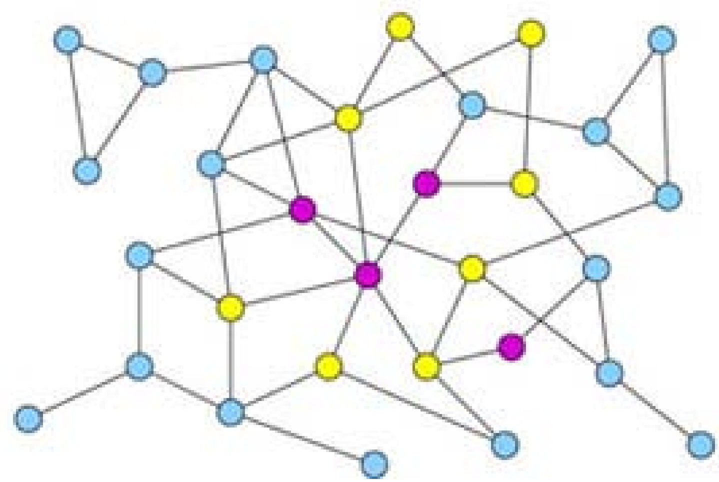
These networks can look more realistic:



Taken from <http://www.esi.utexas.edu/features/Archive/2003/meyers.html>

How does the math on these networks work?

Basic idea is this:

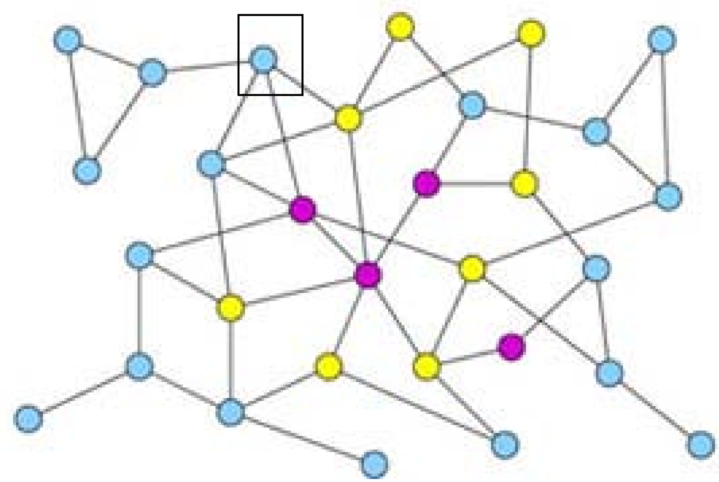


How does the math on these networks work?

Basic idea is this:

Start by picking an individual

We know that guy has 4 contacts



How does the math on these networks work?

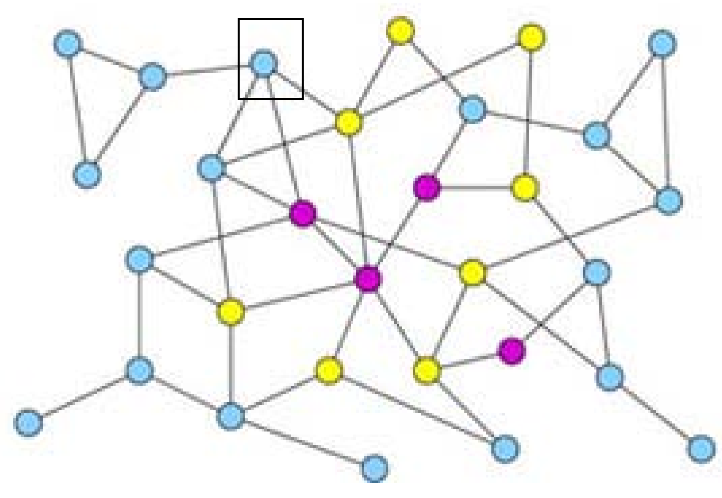
Basic idea is this:

Start by picking an individual

We know that guy has 4 contacts

One contact is R, one is I, two are S

If we know the probability of infection from that 1 infected guy, then we also know the probability that he'll infect his other two susceptible friends



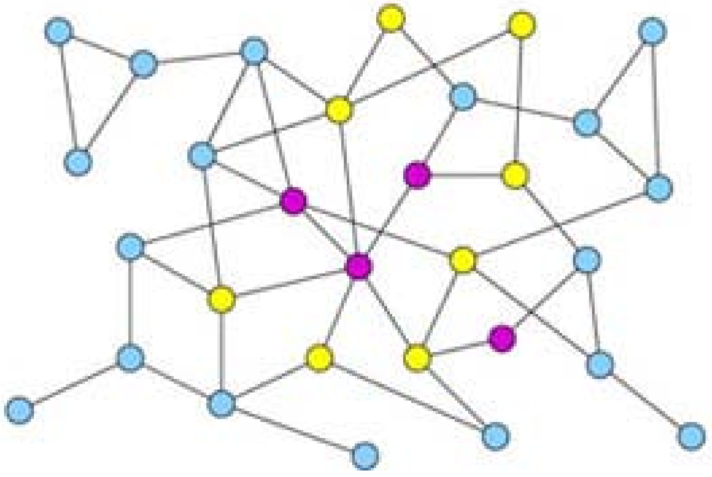
How does the math on these networks work?

So how do we get a full mathematical understanding of the epidemic from this?

We can do this for “the average guy”

We compute the probabilities of contact and infection over time on this known pattern of contacts

That gives us our outbreak

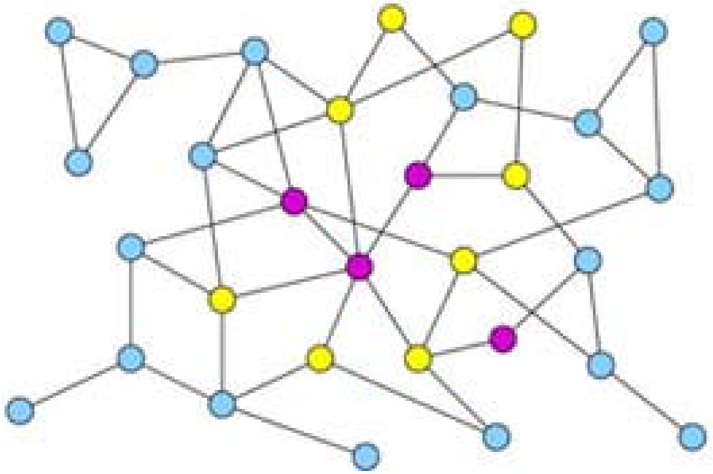


The Compartmental Model and Network Model Won't Always Agree

Notice: Each individual infected guy has fewer susceptibles to potentially infect than in the compartmental model version

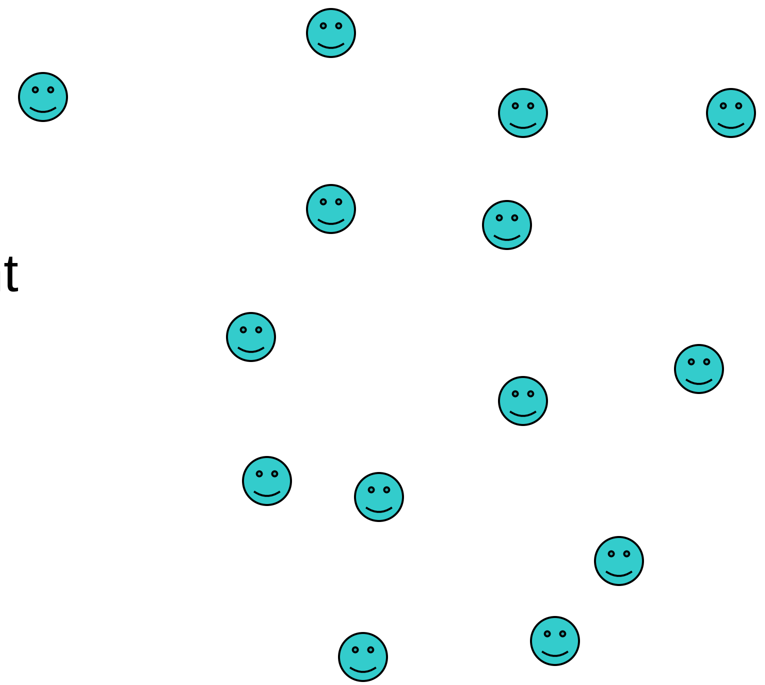
This will depend on the network structure

It can also depend on who starts the outbreak



And there is a third way to model epidemics: Agent Based Models

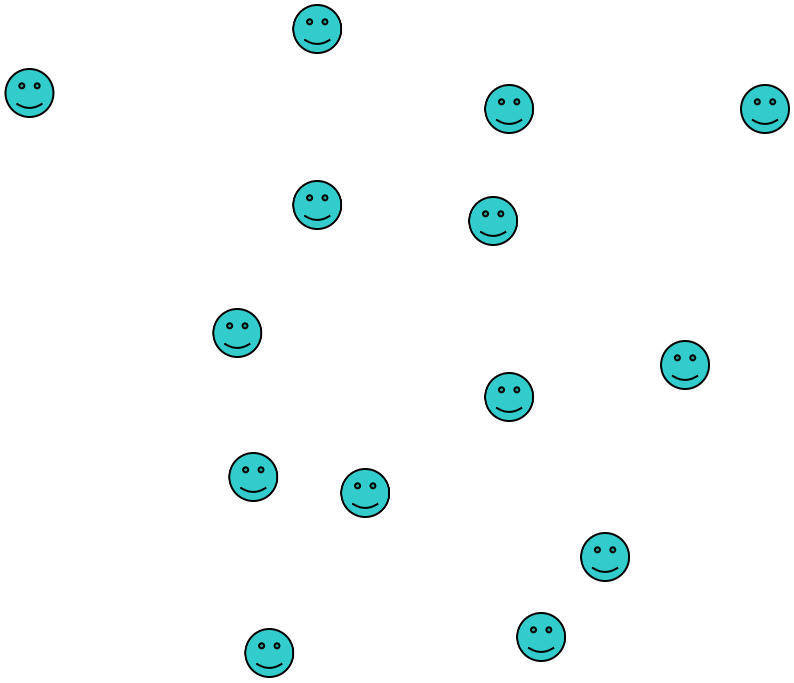
Using computer simulations, we create lots of individuals that all live together in an environment



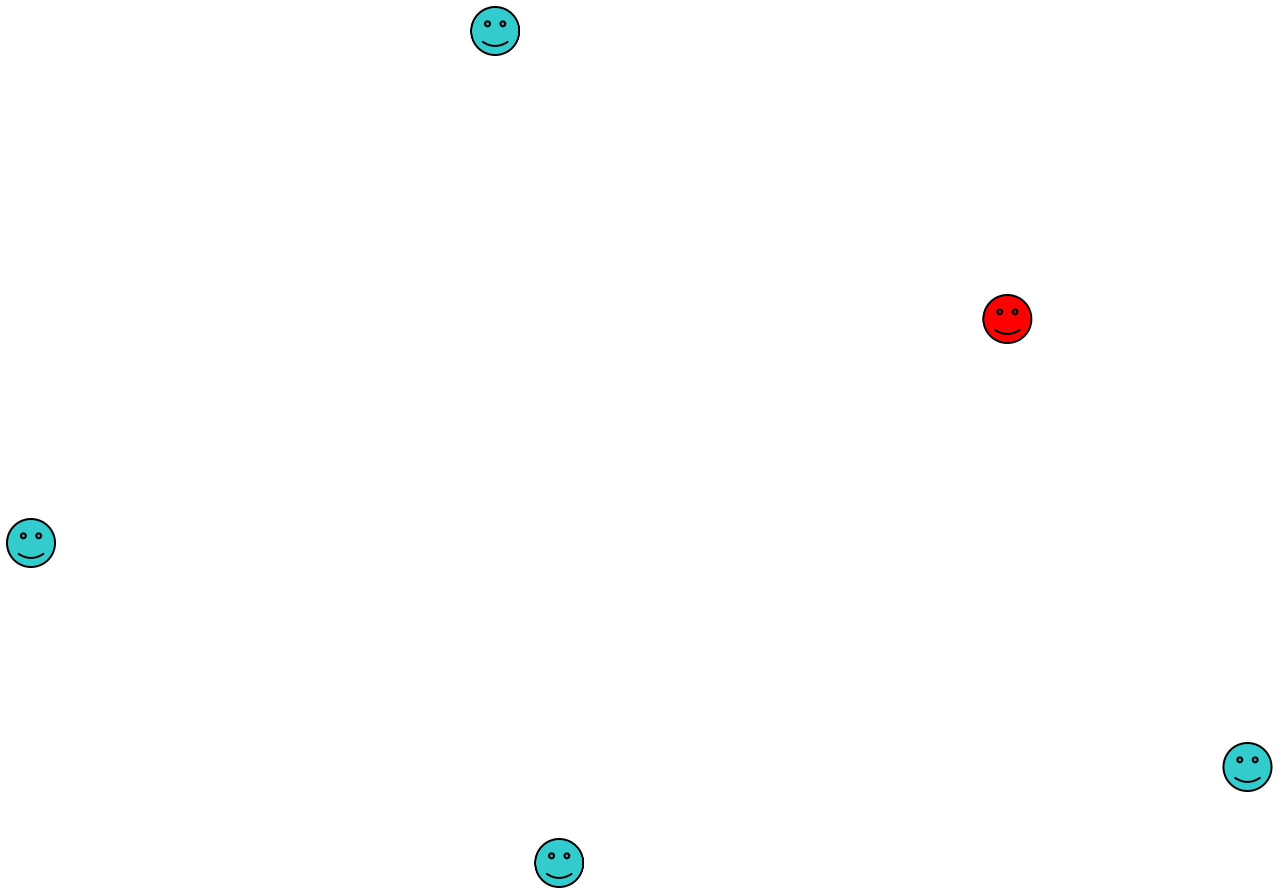
They can:

1. Move around the environment
2. Each have their own susceptibility to disease
3. Interact with each other over time

The individuals effectively run around together:



If an infected individual meets an uninfected individual, there can be disease transmission:



Notice the similarities between AB Models and the other types:

If everyone really does mix at random (like the first slide where they all just ran around), then it's very much like compartmental models, where the compartments just keep track of the colors of the individuals

If it's more like the second example, where groups of people come together, we could draw those contacts explicitly and that would be a network model

So what do AB Models do for us that the others don't?

Usually we don't explicitly decide where and when the individuals go in an AB model – we let the computer decide "at random", possibly influenced by the environmental conditions that can, in turn, be influenced by the positions and states of the individuals

This means that these models include a type of stochasticity that the others don't usually have

(There are ways to include stochasticity in the others - they are complicated and we won't go into them now)

What do all three of these model types have in common?

They all include some representation of human behavior affecting disease spread!

In the compartmental model, the mixing is assumed to be random, and that defines how many individuals move from S into I

In the network model, the mixing is defined by the lines drawn between individuals, and that defines how many other individuals one sick person can infect

In the agent based models, the interactions happen at random, but when and how they happen define who is exposed to disease and for how long

Finally this brings us to the basic difficulty: behavior is **assumed** in these models

People are actually very difficult to predict

As you've seen, we can use math to predict disease spread once we assume human behavior, but how do we find what patterns of behavior we should assume happen?

Right now, we basically guess!

Even if we measure it now, it's likely that people will change how the behave if there is an outbreak of a dangerous disease

How can we begin to understand what assumptions to make in that case?

We can ask people "What would you do if", but people are bad at knowing the answer

This is even more complicated with disease risks:

Infectious disease is one of the ONLY risks in life where both the danger and the defense come from being part of a group

- When are you willing to risk infection to care for a sick child?
- When are you willing to forego seeking medical attention if you will infect the hospital worker?

These aren't easy questions, but they have HUGE impact on the outcome of our mathematical disease models

Now the fun part begins!

In 2005, World of Warcraft had 6.5 million players worldwide – it now has over 9 million

For those of you who don't play, let me introduce you to the world for a few moments

It’s diverse: different types of people play

Working Moms

Students

Doctors

Soldiers

Scholars

Policemen

Politicians

It’s beautiful:

It's dramatic – lots of areas to explore

It's complex – different modes of transport

It has characters from many races

It has ‘world events’: like the lunar festival

It’s highly social: you drink with friends

It’s highly social: you explore in groups

It's highly social: you ride public transportation (like the goblin zepplin)

You face challenges together:

You wouldn't want to meet this guy alone, would you?

People develop long lasting group friendships – relying on each other for months, even years of game play

In 2005, for the first time in an online game, there was an accidental plague in WoW

Here’s what happened: a new area was opened for high level players

In this new area was a new monster – he was large and brutally hard to fight

You needed a team of high level friends just to get to him, and once you found him, you needed to cooperate with your friends to kill him

As part of the challenge of fighting him, he infected you with a disease called Corrupted Blood

Hakkar


[4. LookingForGroup] [Holykiller]: is it a quest from pally trainer?
[4. LookingForGroup] [Ninjaspawn]: yep
[4. LookingForGroup] [Holykiller]: kool
[4. LookingForGroup] [Ninjaspawn]: well at least i know its a quest
[4. LookingForGroup] [Ninjaspawn]: not real sure where its from
[Raid Leader] [Zuli]: see ya later then. it was fun!
You leave the group.
You have left the raid group
Hakkar
Level ?? (Boss)

Here's where things didn't go as planned:

If you were a high enough player to fight Hakkar, Corrupted Blood was unlikely to kill you – it would be annoying, but not deadly

However, the higher level players didn't necessarily wait, as the game had intended, to either be cured of the disease or killed by Hakkar once they had been infected with Corrupted Blood

Some of them left and returned to the cities

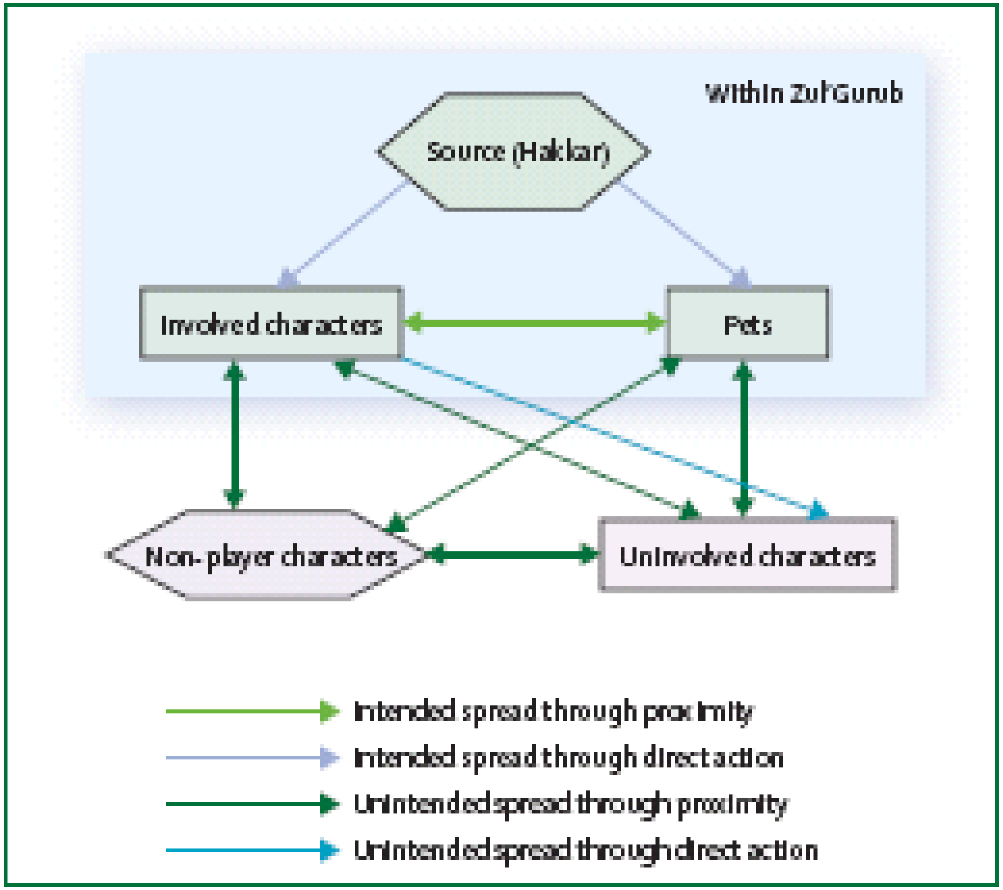
Instantly, lower level players started to die:

Public gathering places were quickly devastated, leaving only bones

The plague had many of the right details to mirror real world epidemics

- It originated from an animal in a remote, uninhabited, jungle region
- It was carried by travelers to urban centers
- It had both human and animal hosts and they passed infection back and forth among each other, sustaining the outbreak
- It was spread from infected to susceptible individuals by close spatial contact
- There were asymptomatic carriers: NPCs

From an epidemiological perspective:



The plague spread out of control

Blizzard (WoW's company) tried to stop it by imposing a quarantine – it failed

Finally, Blizzard had to halt the plague by resetting the game servers

But did we learn anything?

How did players behave during the plague?

Was it close to how people behave in the real world during epidemics?

Somewhat surprisingly: **Yes**

We saw altruism, courage, compliance, fear, suspicion, public concern, non-compliance, opportunism, maliciousness, and even curiosity

Yes, we really DO see maliciousness in real life : e.g. Patient 0; Typhoid Mary

They don't need to be actually malicious for their actions to be the same

Can we learn from what we saw?

Sure

Will it be all we need to know? No

Is it a place to start? Yes

People do behave differently when they know death is temporary, but serious in-game repercussions are still seriously to be avoided

People form strong social bonds in the game and those are very real

Only some people are gamers, so we have to figure out whether non-gamers would behave the same way

Where can we go from here?

Design more in-game disease events-

Maybe not always using deadly plague

Study reactions to see if there are some we haven't thought of in disease models yet (like curiosity)

Study whether people's reactions change based on:

Disease parameters

Rumors

Public Health announcements

Study what affects Risk Perception

So then what? If we learn all these things about behavior?

We go right back to our mathematical models

They can tell us what to expect from disease dynamics, but now we will have a better idea of which human behaviors to assume, based on the types of disease risks

Moral of the story:

Gaming can help save the world!

Work presented was in collaboration with my student, Eric Lofgren

Citation for formal paper:

Lofgren & Fefferman. 2007. The untapped potential of virtual game worlds to shed light on real world epidemics. *Lancet Infect Dis.* 7(9):625-9.

Thanks for inviting me

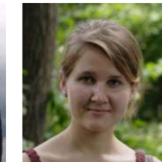
Thank you for your attention and interest

The whole lab group (+/-):

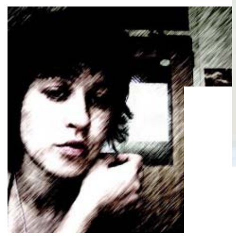














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