Applied Computational Mathematics Lab

EPIDEMIC MODELING · MODULE 1

History of pandemics and modeling

From the plague of Athens to COVID-19, and how models grew up



3 EPISODES

1. Plagues that shaped history
2. From 1918 to COVID-19
3. How epidemic modeling grew up

Based on Chapter 1 of T. Lazebnik, Epidemic Modeling: Principles, Algorithms, and Applications (Academic Press, 2026)

acml.teddylazebnik.com

BEFORE WE START

Warm-up: true or false?

CHECK YOURSELF

(a) The word “quarantine” comes from a forty-day wait for ships.

(b) The “Spanish” flu of 1918 started in Spain.

(c) The first mathematical model of an epidemic came after germ theory.

HOW TO USE THIS

Guess now. (a) and (b) are settled in Parts 1 and 2, (c) in Part 3; all answers are at the end of the deck.

WHY HISTORY FIRST

This module has no equations to solve yet. It builds the picture every later model has to fit: what changes from one pandemic to the next, and what stays hard.

BEFORE WE START

This module's map

PART 1

Plagues before germ theory

Athens, the Black Death, quarantine, cholera and John Snow's map.

PART 2

A century of modern pandemics

1918 flu, HIV, SARS, H1N1, Ebola and COVID-19: one lesson each.

PART 3

How modeling grew up

From counting deaths to SIR, our first simulation, and the model families of this course.

GOALS

By the end you should be able to name the four background conditions that shape any outbreak, give one modeling lesson from each modern pandemic, and explain the epidemic threshold.

TWO WORDS

Epidemic: more cases than expected in one region. **Pandemic**: an epidemic that spreads across countries or continents.

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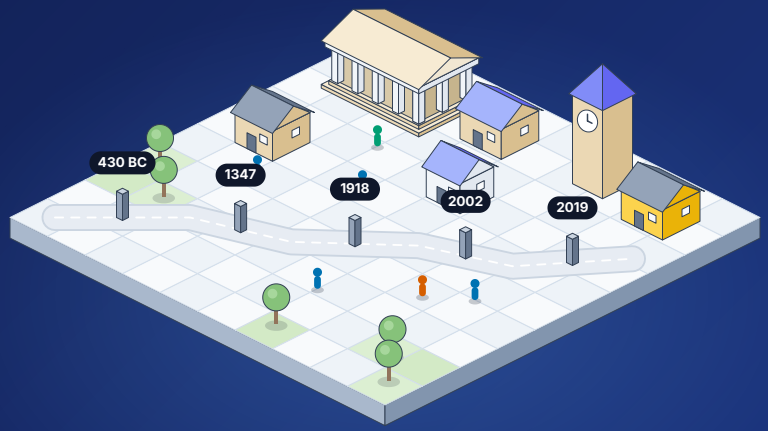
PART 1

Plagues before germ theory

Same problem, different settings.



PART 1 · BEFORE GERM THEORY

Four things that change

1

Connections

How people meet: crowding, trade routes, travel.

2

Daily life

How people live: homes, work, water, food.

3

Beliefs

What people think causes the disease, and so what they try.

4

Tools

What can be done: quarantine, sanitation, drugs, vaccines, data.

IN PLAIN WORDS

Every pandemic is the same basic story: something passes from person to person faster than people can stop it. Change these four, and the same germ writes a different story.

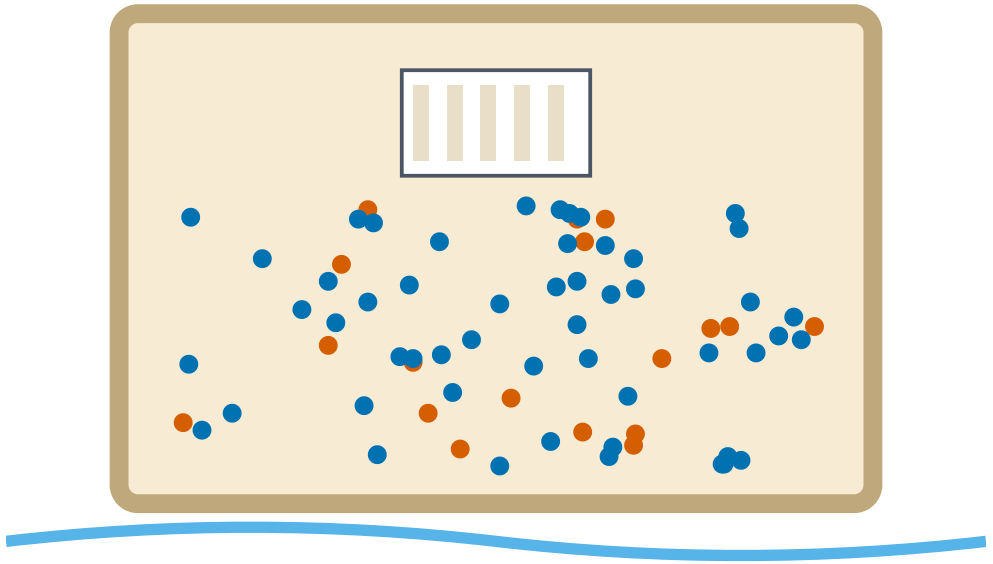
TRY IT

Pick an outbreak you know (for example COVID-19 in your city). Which of the four changed most during it? Write one sentence for each.

PART 1 · BEFORE GERM THEORY

Athens, around 430 BC

- Year two of the war with Sparta. The plan: bring the countryside inside the city walls and let the navy fight.
- A crowded city in summer, sharing water and space: **connections** at their maximum.
- A disease arrives by sea: fever, rash, terrible thirst. A large share of the city dies, including its leader, Pericles.
- Our source is the historian **Thucydides**:
  - he caught the disease himself and survived;
  - he also described the social side: people stopped caring for the sick and stopped following the rules.
- What the disease was is still debated: typhus, smallpox and typhoid have all been proposed.

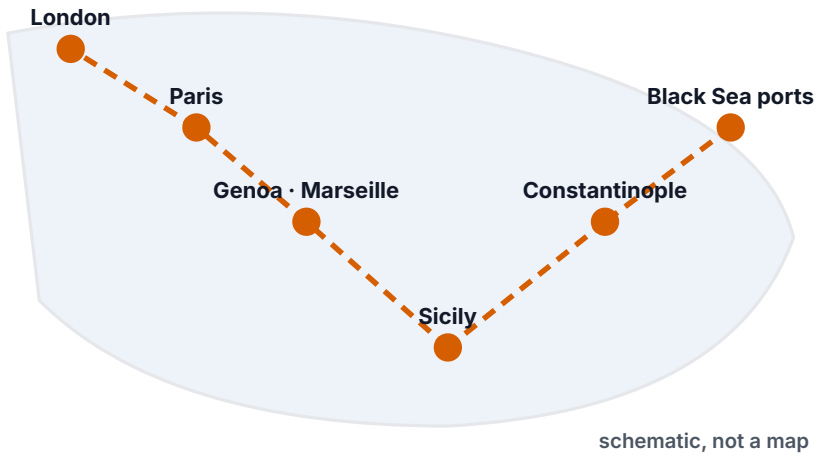


crowded behind the walls (sketch)

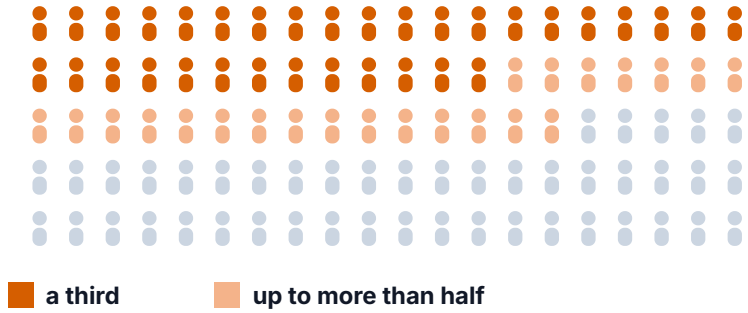
IN PLAIN WORDS

Fear and rule-breaking spread too. Later modules put behavior into the model (Module 2).

The Black Death



schematic, not a map



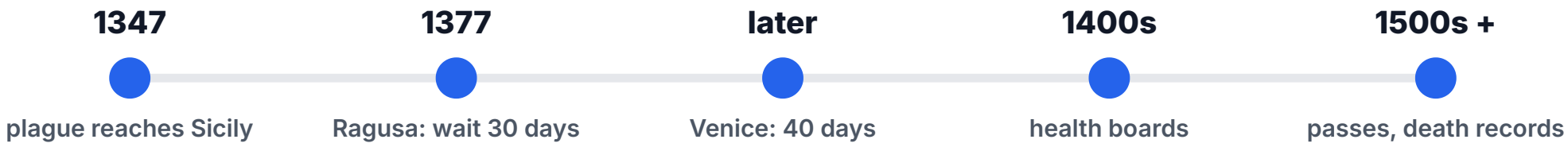
out of every 100 people in Europe: the range of estimates

- 1347: merchant ships bring the plague from the Black Sea to Sicily; in about four years it crosses most of Europe.
- The bacterium *Yersinia pestis* travels with fleas on rats, and sometimes directly between people through the air.
- It follows **trade**: ports first, then rivers and roads. The network of connections shapes the spread.
- Estimates of the toll range from about **a third to more than half** of Europe's population.
- The causes people believed in: bad air (miasma), or divine punishment.

LOOKING AHEAD

A model of this spread would need places and routes, not one well-mixed population. That is Module 4.

Quarantine: acting before understanding



- The port of Ragusa (today Dubrovnik) made ships and travelers from infected places wait 30 days before entering.
- Venice later made it 40 days. *Quaranta* is Italian for forty: the origin of **quarantine**.
- Cities created health boards, health passes and records of deaths: public health started as **government**, not medicine.

IN PLAIN WORDS

They changed the connections without knowing the cause. Sometimes you can act well before you fully understand.

TRY IT

Why might a 30-day wait work against a disease nobody understood? Think about how long a sick traveler stays sick or contagious.

Cholera: the argument about the cause

- Cholera kills through dehydration, sometimes within hours.
- It had long been present around Bengal; from 1817 it travelled, and over the following decades reached Europe and the Americas in several pandemics.
- The big argument of the century was about the cause.

IF YOU BELIEVE…	THEN YOU…
bad air from filth (miasma)	clean streets, drain, rebuild cities
something passes between people (contagion)	stop people at the border, isolate the sick

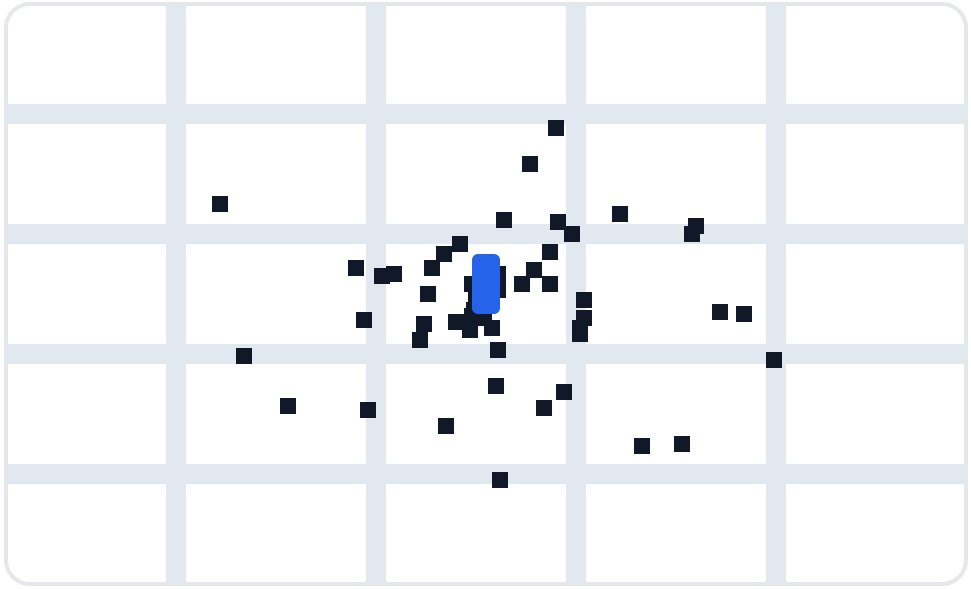
IN PLAIN WORDS

The answer to “what causes it?” decided the policy. A model always carries a belief about the cause, whether or not it says so.

FOOTNOTE

Both sides were partly useful: sewers and clean water cut cholera, and isolation cuts diseases that do pass between people.

John Snow's map



deaths cluster around one pump (illustration, not Snow's data)

- London, 1854: John Snow marks every cholera death in one neighborhood on a map.
- The deaths cluster around one water pump, on Broad Street. The handle is removed; the outbreak there was already fading.
- **Data + place + a hypothesis** pointed at a cause. It is one of the founding pictures of epidemiology.
- The same year, Filippo Pacini saw the bacterium under a microscope in Florence; Robert Koch isolated it in 1883.
- With germ theory, the tools changed: you could target the pathogen, not only the people.

Check yourself: Part 1

CHECK YOURSELF

1. Name the four background conditions and give, for each of Athens, the Black Death and cholera, the one that changed most.

2. Quarantine worked before anyone knew about bacteria. Which of the four conditions did it change?

3. Why did the miasma-or-contagion question matter for policy?

TIP

Answers are at the end of the deck. Try them before you look.

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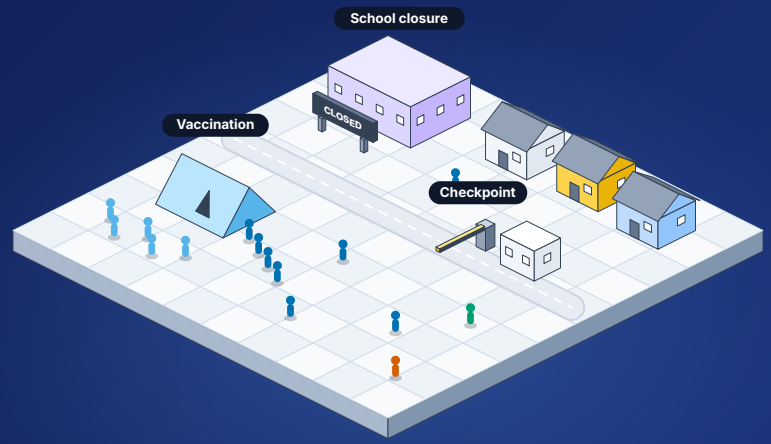
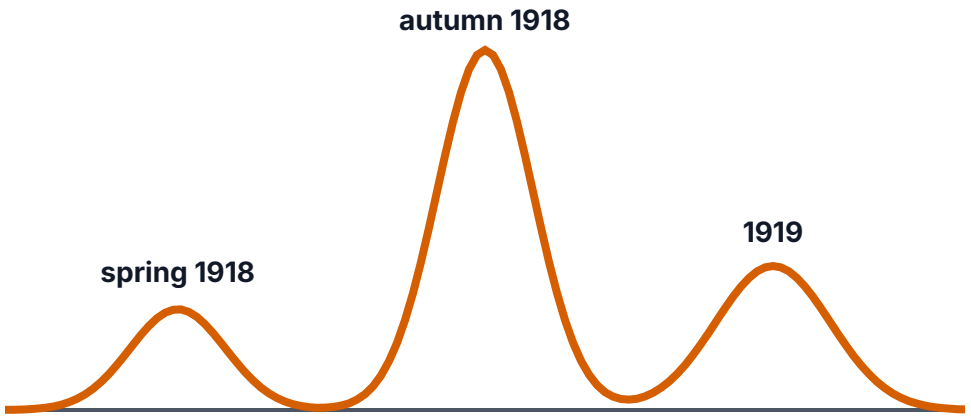
PART 2

A century of modern pandemics

Six pandemics, six lessons for modelers.



1918 influenza



the wave pattern, sketched (not data)

LESSON FOR MODELERS

Waves are normal, and the second one can be worse. A single-peak model can be badly wrong.

- A new influenza virus spreads through armies, ships and cities at the end of the First World War.
- Called the “Spanish” flu, but almost certainly not from Spain: neutral Spain’s press reported it freely.
- It came in waves: a milder one in spring 1918, a much deadlier one in the autumn, more outbreaks into 1919.
- A common estimate is about **50 million deaths**; the range is wide because many countries kept poor records.
- Unusually, many young adults died, not only the old and the very young.

HIV and AIDS

- 1981: clusters of rare infections in young, healthy men; the first recognition of HIV and AIDS.
- HIV is slow: years without symptoms, during which it can be passed on unknowingly.
- It spreads through sex, shared needles, blood, and from mother to child, so **behavior** is at the centre.
- More than 40 million people have died of it (UNAIDS estimate). Since the late 1990s, treatment can keep the virus in check for life.



LESSON FOR MODELERS

Time scales matter. A model built for a two-week flu says nothing about a disease that unfolds over a decade.

PART 2 · MODERN PANDEMICS

SARS, 2002–03

- November 2002, southern China: a new coronavirus causes severe pneumonia.
- February 2003: one infected traveler stays at a hotel in Hong Kong; other guests carry the virus to several countries within days.
- Hospitals become hot spots; health workers are a large share of the cases.
- The World Health Organization counted about **8,000 cases and nearly 800 deaths**; by July 2003 it was contained.

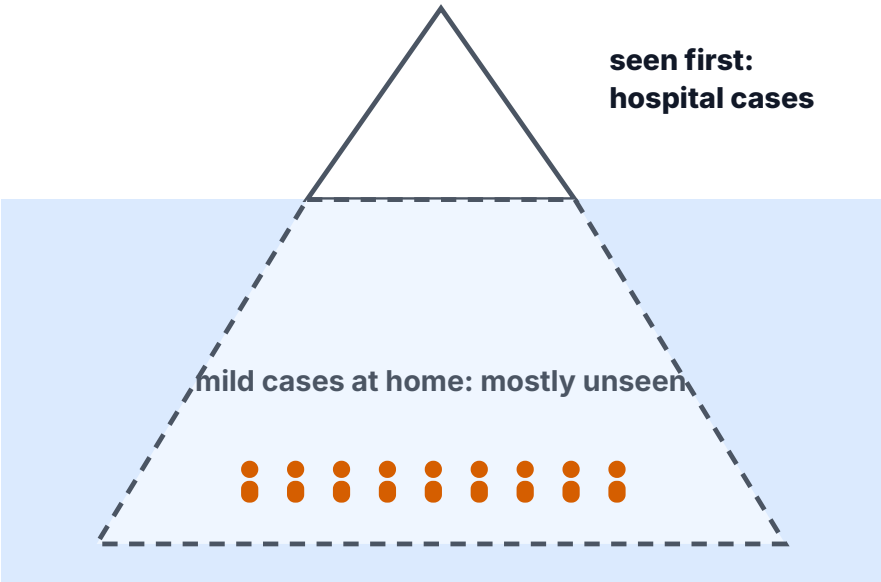
HOW IT WAS STOPPED

No vaccine and no drug: isolation, contact tracing and quarantine, done fast. Old tools still work when transmission is mostly after symptoms start.

LESSON FOR MODELERS

A few events and places can drive most of the spread. Average-person models miss this; networks and agents (Modules 4 and 6) don’t.

H1N1 influenza, 2009



- April 2009: a new H1N1 influenza virus appears in Mexico and the United States, mixing genes from several flu lineages.
- June 2009: the World Health Organization declares the first flu pandemic of this century.
- Early on, nobody knew how deadly it was. The first numbers came from hospitals, which see the sickest cases first.
- It turned out milder than many feared.

TRY IT

A made-up example: a hospital reports 10 deaths among 200 admitted cases, but 20,000 people were infected in all. Compare the death share among hospital cases with the death share among all infections.

Ebola, 2013–16



- The outbreak went unrecognized for about three months, long enough to cross borders and reach capital cities.
- Over about two years: more than **28,000 cases and 11,000 deaths** (World Health Organization counts).
- Care for the sick and traditional burials put families in close contact with the virus; changing that needed trust, not only orders.

LESSON FOR MODELERS

The delay between the first case and the first alarm can decide everything, and people's trust is part of the model.

COVID-19

- Late 2019, Wuhan: a new coronavirus, SARS-CoV-2. On 11 March 2020 the World Health Organization calls it a pandemic.
- Lockdowns, masks, school closures, travel bans, and testing at a scale nobody had tried before.
- Vaccines arrived in about a year, including the first approved mRNA vaccines.
- Official reports counted about **7 million deaths**; studies of excess deaths suggest the true toll was about two to three times higher.

MODELS IN PUBLIC

For the first time, epidemic models were on the front page every day: sometimes right, sometimes wrong, always argued about.

LESSON FOR MODELERS

Reported counts are not the truth; they are a measurement of it. Modules 7 and 9 build models of the measurement itself.

What changed, and what stayed

	1918	2020
Connections	ships and trains, weeks to cross the world	planes, a day to cross the world
Tools	isolation, masks, no flu vaccine	tests, genome sequencing, vaccines in about a year, computer simulation
Data	patchy death records	daily dashboards, mobility, wastewater
Beliefs	a new science of viruses, still uncertain	fast science, and fast misinformation

IN PLAIN WORDS

What stayed hard: waves, delays, hidden cases, and people who change their behavior while the epidemic is happening.

TRY IT

For each of the six pandemics in this part, write its one-line lesson for modelers from memory. Then check the slides.

Check yourself: Part 2

CHECK YOURSELF

4. Why can early estimates of how deadly a new disease is be too high?

5. Which feature of HIV makes a short-time-scale model a poor fit?

6. Ebola went unrecognized for about three months. Name two things that delay hurts.

TIP

Answers are at the end of the deck.

GOING FURTHER

For each question, note which of the four background conditions (connections, daily life, beliefs, tools) it is really about.

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PART 3

How modeling grew up

From counting deaths to the families of models.



Counting: John Graunt, 1662

- London published weekly **bills of mortality**: who died, and of what.
- Graunt was the first to add them up systematically and compare: which causes grow, which seasons are worse, how plague years stand out.
- He also estimated how many people survive to each age: an early life table.

THE IDEA

Step one of every model, even today: count carefully, and compare like with like.

TRY IT

A made-up week: 1,200 deaths in all, 420 from plague. The next week: 1,500 deaths, 780 from plague. By how much did plague deaths grow, and did the plague share of deaths go up or down?

A policy model: Daniel Bernoulli, 1760

- The question: inoculation protects against smallpox, but a small share of the inoculated died. Should a whole population do it?
- Bernoulli followed a group from birth: each year some catch smallpox (and some of those die), and the rest stay susceptible.
- Comparing that with a world where everyone is inoculated at birth, he estimated a gain of **about three years** of life expectancy.

IN PLAIN WORDS

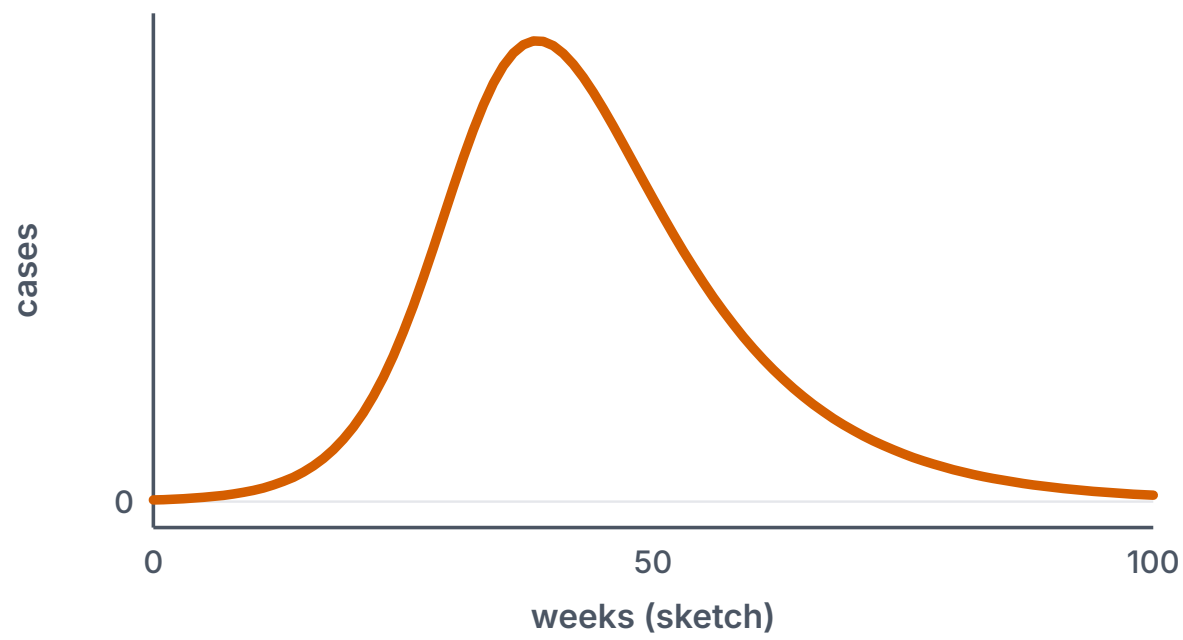
A model, a policy question, and a number to help decide. That is still the job.

LOOKING AHEAD

Bernoulli's method is the ancestor of every "what if we vaccinate?" calculation in Module 10.

Curves and maps: Farr and Snow

- In 1800s England, William Farr turned death registers into curves, and tried to predict an epidemic's rise and fall from its early weeks.
- John Snow placed deaths on a map and found the pump.
- Together: **routine data**, a **shape over time**, and **a place**. Every surveillance system still has these three.



A rise-and-fall shape (our SIR run), not Farr's data.

The big idea: mass action

$$\text{new infections per day} \propto S \times I$$

- New infections depend on how often **susceptible** and **infected** people meet.
- William Hamer used it for measles in 1906.
- Ronald Ross used it for malaria and showed you don’t need to kill every mosquito, only enough to push transmission below a threshold.

WHY “MASS ACTION”?

The name comes from chemistry: there, a reaction’s speed is proportional to the concentrations of what reacts. In epidemics, the “reactants” are susceptible and infected people meeting.

IN PLAIN WORDS

Double the infected, and new infections double; halve the susceptible, and they halve too. That one product drives most of this course.

TRY IT

In a made-up town, 900 people are susceptible and 10 are infected, and there are 18 new infections today. If tomorrow there are 800 susceptible and 20 infected, roughly how many new infections would mass action predict?

Kermack and McKendrick, 1927



$$\frac{dS}{dt} = -\beta SI, \qquad \frac{dI}{dt} = \beta SI - \gamma I, \qquad \frac{dR}{dt} = \gamma I$$

- β: transmission rate. γ: recovery rate, so $1/\gamma$ is the average time infected.
- S, I and R are shares of the population; they always add up to 1.

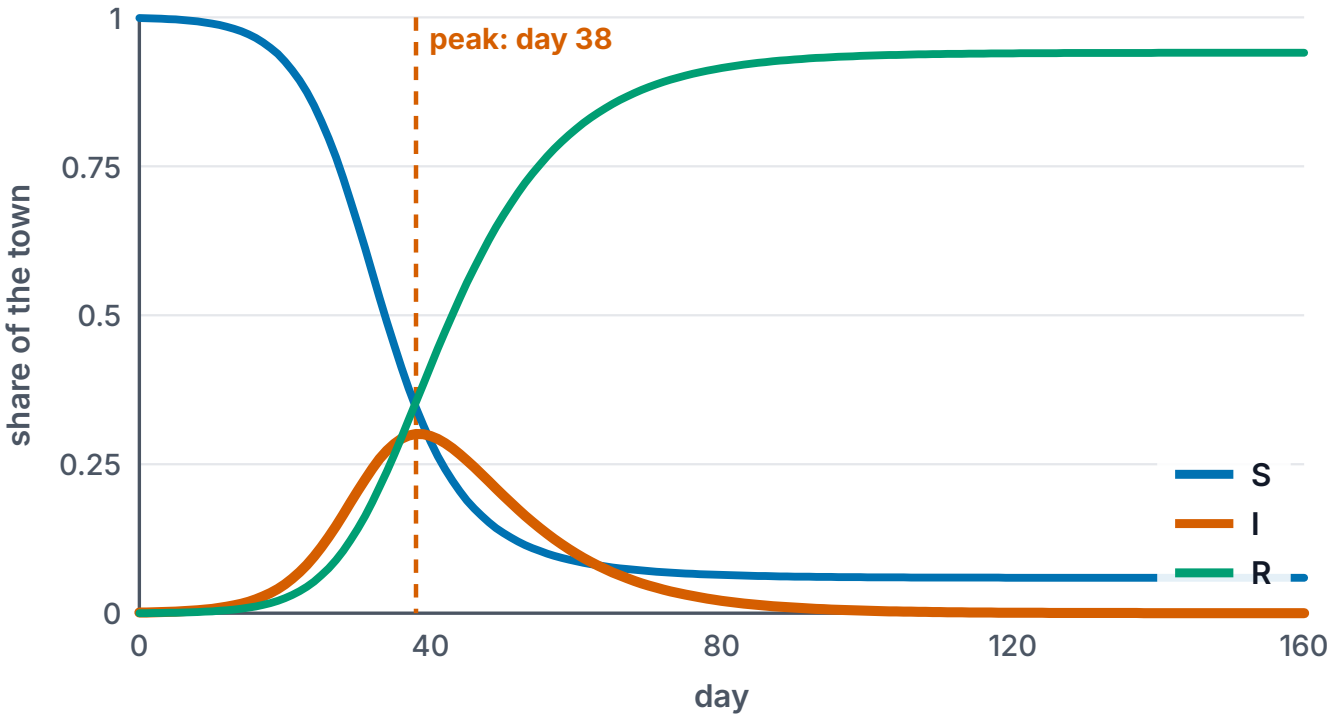
THE THRESHOLD

At the start almost everyone is susceptible, so each case infects about $R_0 = \beta/\gamma$ others. If $R_0 < 1$ the outbreak dies out; if $R_0 > 1$ it takes off.

IN PLAIN WORDS

Module 3 is all about this model, its family, and R_0.

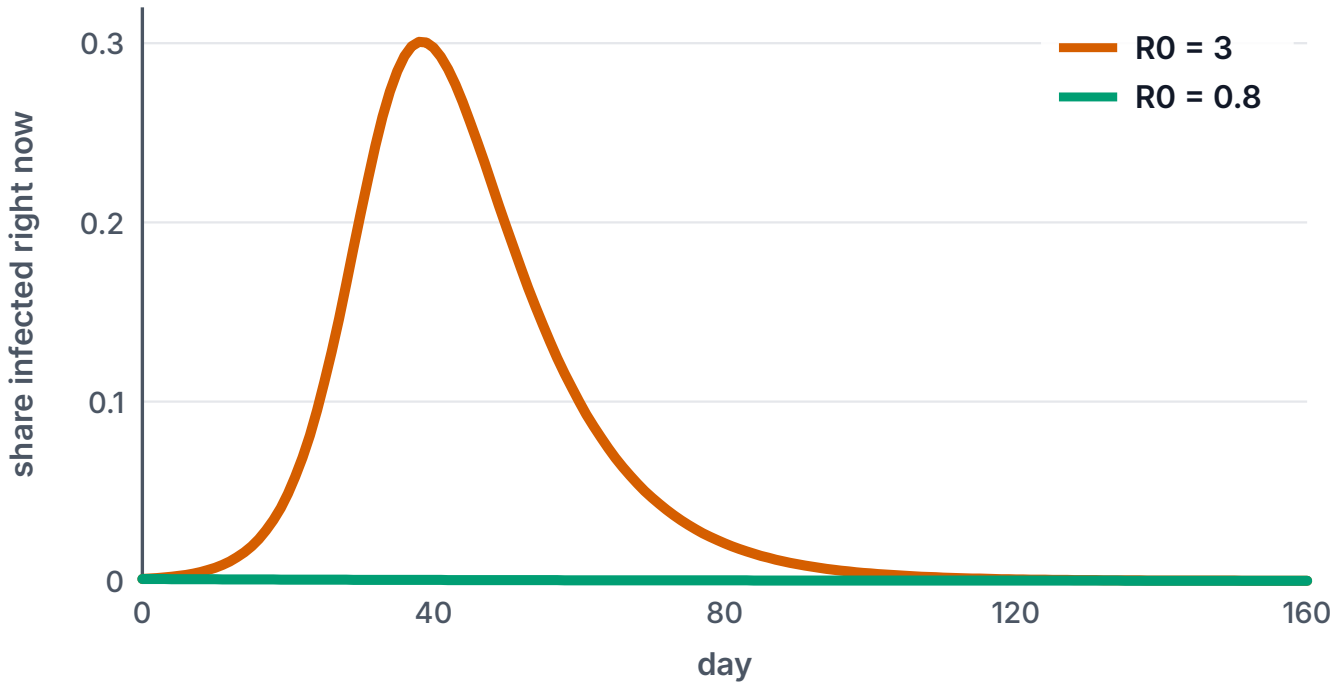
Our run: an SIR town



- A town of 1,000 people, one initial case. $\beta = 0.3$ per day, recovery after 10 days on average ($\gamma = 0.1$).
- So $R_0 = 0.3 \times 10 = 3$.
- Infections peak around day 38, when about 30% of the town is infected at the same time.
- By the end, about 94% of the town has been infected.

Our run: production/explains/sims/epi_m01_sims.py.

Our run: below the threshold



- Same town, same first case, but $\beta = 0.08$: $R_0 = 0.8$.
- The outbreak fizzles: only about 0.5% of the town is ever infected.
- Three letters, two equations, and already a policy message: **push R below 1**.

TRY IT

With recovery after 10 days, what transmission rate β puts the town exactly at the threshold?

Surveillance, computers, and new data

AFTER 1945

Surveillance as an institution

Agencies collect disease reports every week, in the same format.

COMPUTERS

From equations to simulations

Thousands, then millions, of simulated individuals.

THIS CENTURY

New data streams

Search queries, phone mobility, wastewater, and virus genomes read in days.

IN PLAIN WORDS

New data doesn’t replace the old questions: who is missing from it, how biased is it, and who agreed to share it?

A WARNING

Big data can mislead: a famous search-based flu tracker overestimated flu seasons once people’s search habits changed.

The model families

FAMILY	KEY IDEA	STRENGTH	WEAKNESS	TYPICAL USE
Compartmental (deterministic or stochastic)	groups like S, I, R; rates between them	clear, fast, easy to analyse	everyone in a group is treated the same	R_0, thresholds, scenarios
Spatial and network	places, travel and who meets whom	captures where and how it moves	needs contact or mobility data	travel, cities, superspreading
Agent-based	every person simulated with their own rules	realistic, detailed policies	hungry for data and computer time	targeted interventions
Data-driven and machine learning	patterns learned from the numbers	good short-term forecasts	weaker at explaining why	nowcasts and forecasts

IN PLAIN WORDS

None of them is the best. Each one is the right tool for some question; choosing well is half the skill.

Choosing a model

QUESTIONS TO ASK FIRST

1. What decision will the model support?
2. What data do we have, and how reliable is it?
3. How fast do we need an answer?
4. Does behavior, place or individual detail matter for this question?
5. How will we check the model against reality?

THREE QUICK EXAMPLES

Early in an outbreak, with only case counts: a simple compartmental model. Planning school reopening in one city: an agent-based model. Forecasting next week's hospital load: a data-driven model, checked against a mechanistic one.

TRY IT

A city wants to know whether closing schools for two weeks is worth it. Which family would you start with, and why?

PART 3 · HOW MODELING GREW UP

The road ahead

MODULE 2
Beyond the virus

MODULE 3
Compartmental models

MODULE 4
Space

MODULE 5
Strains

MODULE 6
Agents

MODULE 7
Data-driven models

MODULE 8
Calibration

MODULE 9
Surveillance and data streams

MODULE 10
Interventions

MODULE 11
Uncertainty and comparison

MODULE 12
Computation

MODULE 13
What comes next

IN PLAIN WORDS

History done. From here on, we build: first the world around the virus, then the models themselves.

Check yourself: Part 3

CHECK YOURSELF

7. State the mass-action idea in one sentence.

8. In an SIR model with recovery after 5 days on average and $\beta = 0.5$ per day, what is R_0? Will the outbreak take off?

9. Give one strength and one weakness of agent-based models.

TIP

Answers are on the next slides.

Answers: warm-up and Part 1

- **(a)** True: Venice's forty days (*quaranta*). **(b)** False: neutral Spain reported it freely; it almost certainly started elsewhere. **(c)** False: Bernoulli's smallpox model (1760) came more than a century before germ theory.
- **1.** Connections, daily life, beliefs, tools. Athens: connections (crowding inside the walls). Black Death: connections (trade routes), and later tools (quarantine). Cholera: beliefs, then tools (germ theory, clean water).
- **2.** Connections: it cut contact between incoming travelers and the city.
- **3.** The belief decided the action: cleaning streets for miasma, border controls and isolation for contagion.

Answers: Parts 2 and 3

- **4.** The first cases counted are the severe ones (in hospital); mild cases at home are missed, so deaths divided by known cases is too high.
- **5.** Years without symptoms, during which people can pass it on: the dynamics unfold over a decade, not weeks.
- **6.** Any two of: chains of transmission grow unseen; the outbreak crosses borders; it reaches cities; the response starts from a bigger outbreak.
- **7.** New infections are proportional to how often susceptible and infected people meet: roughly βSI.
- **8.** $\gamma = 1/5 = 0.2$, so $R_0 = 0.5/0.2 = 2.5 > 1$: it takes off.
- **9.** Strength: realistic individuals and detailed policies. Weakness: needs a lot of data and computer time, and is hard to calibrate.

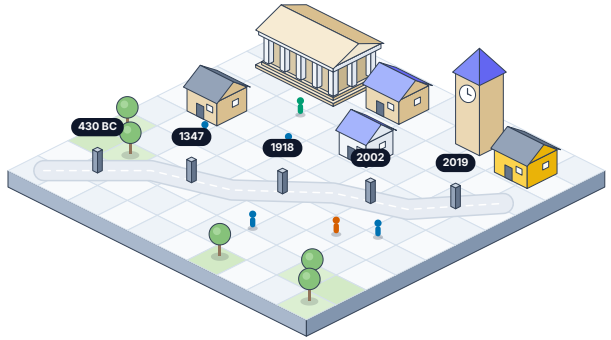
TRY-IT ANSWERS

Try-it answers: Graunt: plague deaths grew by 360 (from 420 to 780), and the plague share rose from 35% to 52%. Mass action: $18 \times (800 \times 20)/(900 \times 10) = 32$. Threshold: $\beta = \gamma = 0.1$ per day. H1N1: 5% of hospital cases versus 0.05% of all infections.

CREDITS

Sources and credits

- This deck accompanies Chapter 1 of T. Lazebnik, Epidemic Modeling: Principles, Algorithms, and Applications (Academic Press, 2026), the course textbook. It follows the chapter's topics in our own words; no text, figures or tables are copied from the book.
- The text, figures, examples and simulations were written, drawn and run for ACML; nothing is copied from the book. Numbers labelled "our run" come from our own code; counts from agencies and papers are credited where they appear.
- Counts quoted from agencies: SARS cases and deaths and Ebola cases and deaths (World Health Organization); HIV deaths (UNAIDS). Other numbers are commonly cited historical estimates and are labelled as such.
- Companion videos: **Epidemic Modeling**, module 1, episodes 1–3. More from the lab: acml.teddylazebnik.com



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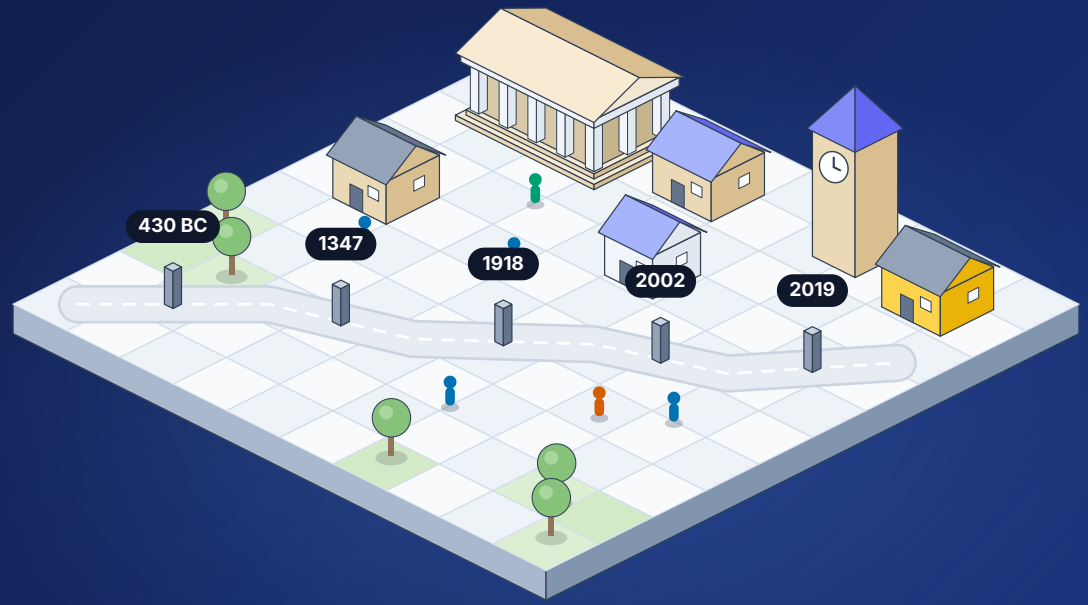
Module 1 complete

END OF MODULE 1

History of pandemics and modeling



YOU COVERED

- Plagues that shaped history
- From 1918 to COVID-19
- How epidemic modeling grew up

UP NEXT · MODULE 2

Beyond the virus

Biology, psychology, economics and governance

Based on Chapter 1 of T. Lazebnik, Epidemic Modeling: Principles, Algorithms, and Applications (Academic Press, 2026)