Causality in the Time of Cholera: John Snow and the Process of Scientific Inquiry

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What Causes Cholera? Hugely Important in 1850s London

Horrendous way to die – dehydration, convulsions, blue skin, die within hours

Scourge of mid-1800s London – 1831-32 6,526 dead; 1849 14,137; 1853-54 10,738

Massive uncertainty as to cause

- Bad air (miasma); bad breeding (poverty); bad ground (plague pits)

Huge public health question – one man knew the answer, but nobody listened:

- John Snow & fecal-oral transmission – effort to prove causal theory

Puzzle – Evidence Supported Snow's Theory, Not Adopted

Snow, in 1849 and again 1855, provided strong evidence

- Evidence, and current-day discussions, center around "causal water"
- Consistent with Neyman-Rubin *potential outcome* framework – ***but failed to convince public & medical health establishment***!
- Snow credited with first use of difference-in-differences & randomization as IV

Evidence supports Snow's theory, contradicts alternatives,

Why did Snow's evidence fail to convince?

Changing minds required additional information

- Preponderance of evidence
- Whitehead discovered plausible mechanism for contamination of pump (baby girl Frances Lewis)
- Farr visited Pacini (first to identify *vibrio cholerae*)

Wider Context & History: Identification and Causal Analysis

What we have *not* done (yet) – Placed this in the wider history of causal analysis

Within economics

- Friedman ("Methodology of Positive Economics", *Theory of the Consumption Function*)
- Pinto & Heckman "The Econometric Model for Causal Policy Analysis"
- History: Many others: Marshall, Koopmans, Frisch, Wrights

Statistical and Data Science Approaches:

- Neyman-Rubin, Pearl & *Do-Calculus*

Rational Reconstruction of History

We undertake *rational reconstruction* of competition among theories in 1850s

- Snow used multiple strands of evidence (some statistical, some not)
- Alternatives adjusted by incorporating "causal water"

Helps us understand

- Why fecal-oral theory superior
- How alternatives (rationally) survived
- How to demonstrate a causal explanation

By final London cholera outbreak (1866) fecal-oral theory widely – but not universally – accepted

- *Lancet*, Privy Council (J.N. Radcliffe) and Parliament (William Farr)

Recognize the Potential Outcome view of causality is insufficient for building a causal explanation (understanding the causes of cholera)

- We propose an *Abductive Process of Scientific Inquiry* using
- Peirce's *Three Stages of Inquiry* (Abduction, Deduction, Induction) and Lakatos's *research programmes* and *sophisticated falsification*

Why John Snow and 1850s Cholera?

Three reasons:

1. Rollicking Good Tale – full of heroism, death, and statistics
2. Statistics & Instruction – The data are simple but the analysis demonstrates multiple data analytic tools we use today
   - combining maps and data (GIS or geographic information systems)
   - regression and error analysis
   - difference-in-differences regression
   - natural experiments and randomization
3. **Template for Abductive Process of Scientific Inquiry** – illuminates
   - how to marshal evidence in support of causal explanation
   - why (rationally) Snow's theory was not immediately adopted

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Cholera – Disease of Poor Sanitation

What is Cholera?

- Vibrio Cholerae – bacterium that infects the small intestine of humans
- Causes severe diarrhea (& vomiting) that drains fluids
- Death from dehydration & organ failure
- Oral Rehydration Therapy highly succesfull (roughly 1960s)
  - In case you ever need it, here's the recipe – 1 liter boiled water, 1/2 teaspoon salt, 6 teaspoons sugar, mashed banana (potassium)

Cholera thrives in crowded cities with poor sanitation

- Transmitted through (inadvertent) ingestion of fecal matter
- When cholera exits one victim, needs to find a way into gut of others
- Commonly contaminated water – recycling (drinking) sewage
- Victorian London was an ideal playground for cholera to thrive

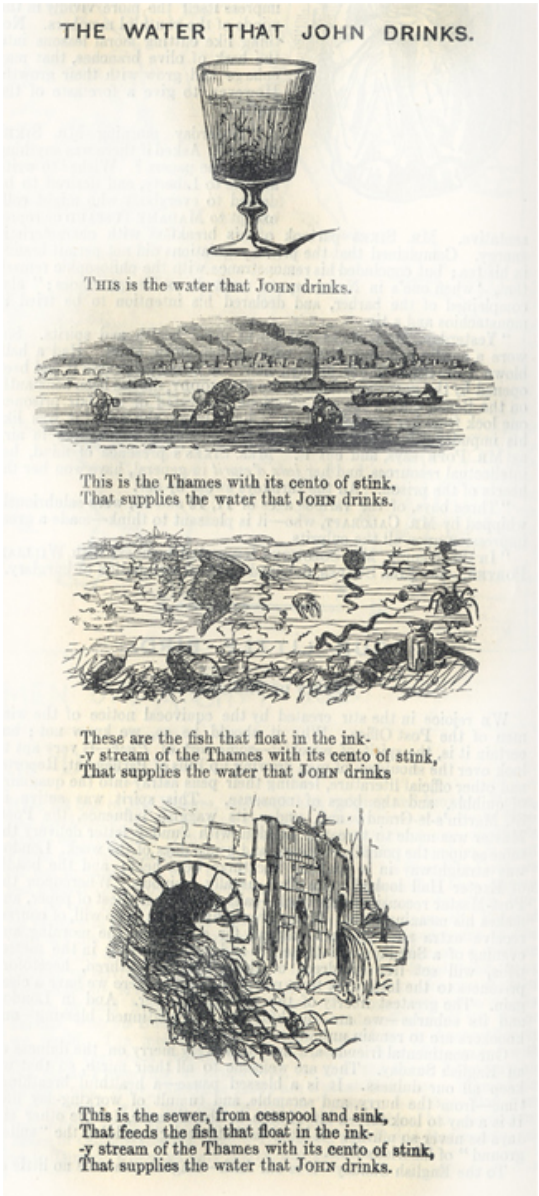
Cholera Loved Victorian London

Victorian London was an ideal playground for cholera

- Mid-1800s London was dirty, smelly place with no organized sewage treatment
- Efforts to improve sanitation made things worse
  - cesspools relatively safe – did not provide access to thousands of guts
- Public Health Act of 1848 required houses to connect to sewage lines
  - helped clean up streets, flushed filth to Thames
- By mid-1800s, cholera had easy access from the gut of one to thousands of victims

Contemporaries were aware of dirty water (*Punch* 1849)

- But water not recognized as vector for cholera



Solution – Construction of Bazalgette "Outfall Sewers"

Sewers that sloped towards outfalls (discharge points) lower on the Thames

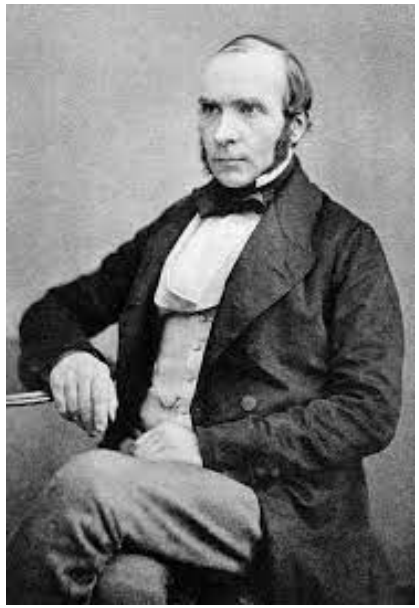
- Construction started (under Bazalgette) 1859, response to 1858 "Great Stink"
- Embankments along Thames – what we see today
  - Embedded discharge pipes – still used today (?)
  - Decreased width, increased flow – scouring effect
- Moved sewage downstream, below London & water in-take

One final outbreak, 1866, limited to east London, last area unserved by sewers

John Snow's Research & Publications

Doctor – pioneer in anesthesia & medical hygiene

- Provided Queen Victoria with anesthesia during childbirth



Research and writing on Cholera

- 1849: "On the Mode of Communication of Cholera"
  - Laid out theory and evidence for waterborne transmission
- 1855: "On the Mode of Communication of Cholera"
  - Substantially expanded, additional evidence and argument (DiD & randomization)
- 1856: "Cholera and the water supply in the south district of London in 1854"
  - "Actual vs predicted" for other causes of cholera

John Snow's 1849 Theory & 1855 Evidence

1849: Snow developed theory of infection & transmission

- Based on medical knowledge and study of single events – Horsleydown & Albion Terrace

Fully-developed & modern theory of disease

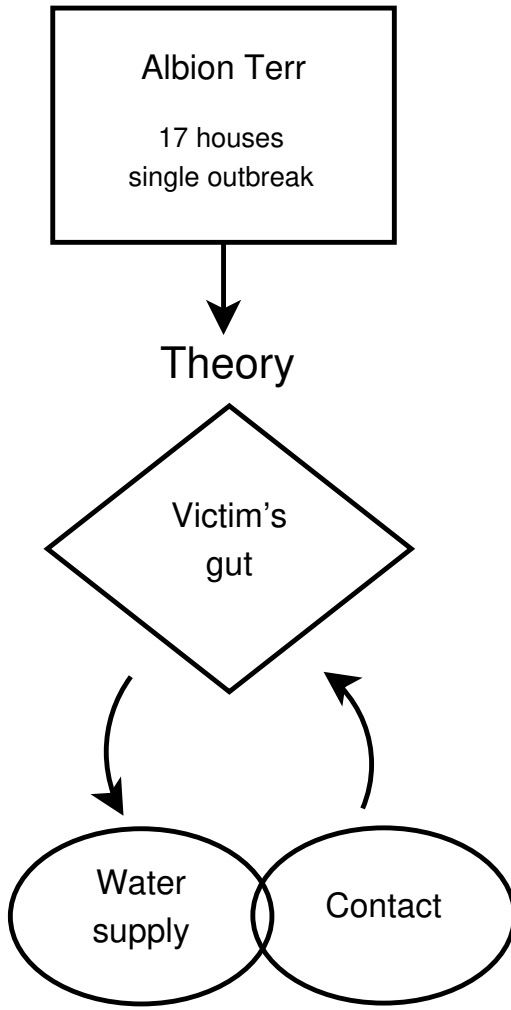
- Infects & reproduces in the small intestine
- Exits from victim, another through contact or water

Implications for patterns of infection, across scales

- Person-to-person (normal)
- Neighborhood (localized water, explosive)
- Municipal (drinking water, widespread)

Snow's work grounded by theory

> *Snow had a good idea – a causal theory about how the disease spread – that guided the gathering and assessment of evidence. (Tufte)*



1855: evidence & argument to convince skeptics – effort at *Falsification*

Alternative Theories – Airborne (Inhaled)

For our purposes – predicting cholera observations – alternatives were **Airborne**

- One version was **Miasma** – general atmospheric influence
- For all, cholera poison was airborne and (generally) inhaled

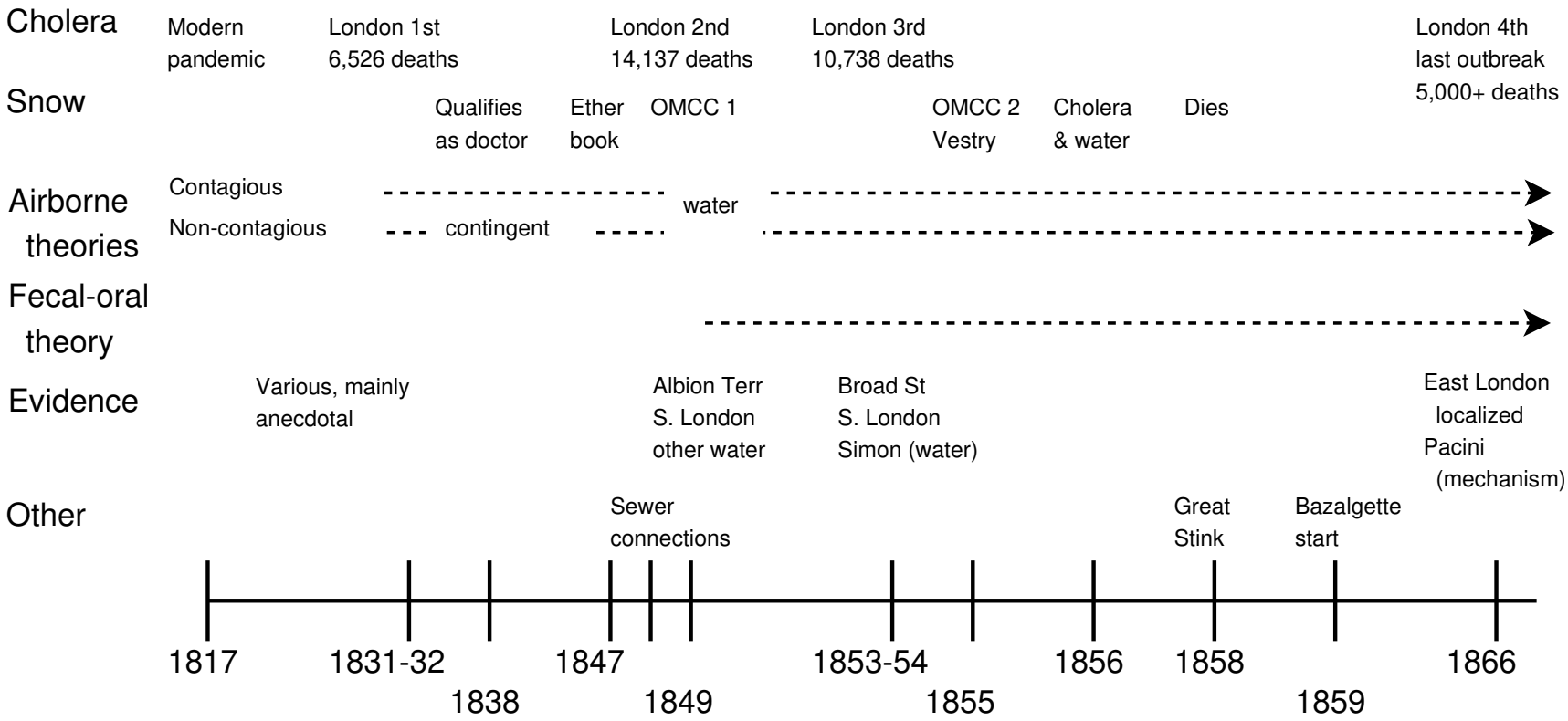
Important debates, *which we can largely ignore* – **airborne** is important

- Contagious: transmitted person-to-person
- Non-contagious: atmospheric, general or localized environmental factors
- Contingent-contagion: introduced 1830s due to contradictory observations
- Localization: non-contagious, specific local factors (e.g. dampness)

All theories posited **predisposing causes** and **susceptibilities**

- Crowding, poverty, dampness, filth (sewage, smells), graveyards
- None absolutely crazy – often correlated with cholera (and dirty water)
- Elevation important (empirically and historically – Farr)

Timeline – For Events, Snow, Theories, Data



1858 – Snow's theory not widely accepted – his Lancet obituary, no mention of cholera

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Standard Approach – "Causal Water" & Potential Outcome

1850s – Strong evidence supporting water as causal

- John Snow, but many others (John Simon, John Sutherland, Rev. Henry Whitehead, William Farr) demonstrated strong evidence

They did not have statistical tools, but recognized causality issues

- Snow used a nascent difference-in-differences, Simon recognizable DiD.
- Snow used randomization as IV
- Discussion of effect and importance of randomization by Farr (and Snow) is quite modern

Seems clear-cut case of "Falsification" & "Refutation"

- Airborne theories predict infection by breathing
- Fecal-oral theory predicts infection by drinking contaminated water

Yet "causal water" did not move medical establishment to fecal-oral theory

- Presented as example of "smart people cling[ing] to an outlandishly incorrect idea despite substantial evidence to the contrary" (Johnson)

Snow's "Grand Experiment" – Water Supply Changes

Two water companies served south London – Southwark & Vauxhall Co and Lambeth Co. – 486,936 customers, 300,000 **intimately mixed**

- In 1830s & 1840s companies competed for customers, often on same street
  In many cases a single house has a supply different from that on either side. Each company supplies both rich and poor, both large houses and small; there is no difference in the condition or occupation of the persons receiving the water of the different companies. (Snow 1855 p 75)

1849 epidemic

- Both companies drew water from low in the Thames – near Vauxhall bridge

1852

- Lambeth Company moved source to Thames Ditton (upstream of London)
- In response to Act of Parliament, requiring move (by 1855)

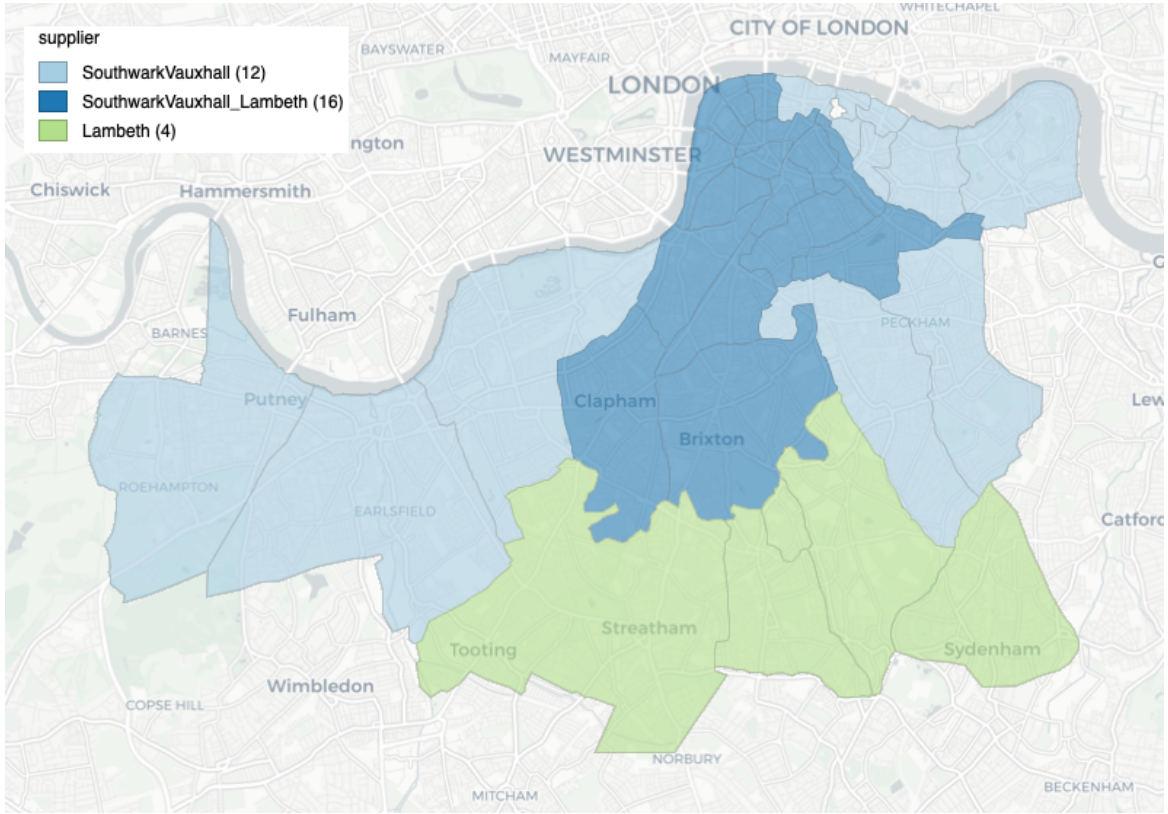
1854 epidemic

- Southwark & Vauxhall Co supplied dirty water
- Lambeth Co supplied cleaner water

32 Subdistricts, 12 S&V only, 16 joint, 4 Lambeth

Registration Districts & Sub-Districts – Need to keep straight

- Deaths collected weekly by Registrar-General, by District & Subdistrict
- In this region of South London, 32 sub-districts
- Some supplied S&V only, others joint
- DiD: compare "S&V only" vs "joint"
- Mixing & randomization: ideally, compare within "joint"



- "First 12" (light blue) – Southwark & Vauxhall Water Co only – dirty water 1849 & 1854
- "Next 16" Mixed or Joint (dark blue) – Southwark & Vauxhall Co *and* Lambeth Water Co – 1849 dirty water, 1854 part dirty (S&V) & part clean (Lambeth)
- "Final 4" (green) – Lambeth Water Co only – not relevant, not supplied in 1849

Snow's Diff-in-Diffs – Before v After, Treated v Control

Comparing the S&V-only subdistricts vs the Jointly-supplied subdistricts

- Interestingly, Snow did not convert deaths to rates – missed an opportunity
- Large treatment effect, but need to evaluate statistical significance

Mortality Rates 1849 & 1854, Summary Snow 1855 Table XII

	1849 Deaths per 10,000	1854 Deaths per 10,000	Ratio 1849 - 1854
Always Dirty – Southwark & Vauxhall Water Company Only ("First 12" subdistricts)	134.9 dirty, S&V only	146.6 dirty, S&V only	0.92 diff in time
Dirty / Clean – Joint Southwark & Vauxhall and Lambeth Companies ("Next 16" subdistricts)	130.1 dirty, joint	84.9 (partial) clean	1.53 diff in time & treatment
Ratio: Next 16 less First 12	0.96 diff in region	1.73 diff in region & treatment	1.67 (partial) treatment

Modern re-analysis

- Confirms causal effect using extended DiD (and randomization)

Many Contributed Evidence for "Causal Water"

1849:

John Sutherland – Board of Health official

- 1849, Hope Street, Manchester, 90 houses, 25 deaths.
- 30 used pump water, 25 deaths; 60 used other water, 0 deaths

William Farr – head of statistics, General Register Office

- "Dr. Snow is unfortunately able to show that this excremental distribution [waterborne] ... is possible to a very considerable extent"
- Table (1853 publication) showing deaths in 1849: "impurity of the waters .. is in nearly a direct proportion to the mortality from cholera"

1854

John Simon Medical (Officer of Health for the City of London)

- DiD (more explicit than Snow's): "final solution of any existing uncertainty as to the dangerousness of putrefiable drinking-water"

Rev. Henry Whitehead (working on Broad St, ultimately ally of Snow's)

- Those who drank vs did not drink – essentially 2x2 contingency table

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"Causal Water" Wonderful, But Useless

Snow's work wonderful example of causal analysis

- Good for teaching – simple data, important social problem, valuable techniques (DiD & randomization), clean results

But proving water was causal had little impact – fecal-oral theory not widely accepted in 1850s.

Why?

Need deeper view of scientific inquiry than Neyman-Rubin potential outcome

- We are not minimizing importance or value of potential outcome framework
- It is a crucial component – but only a component – of overall abductive scientific inquiry

Airborne Theories Adopt "Causal Water"

Alternatives – Airborne Theories – adopted water as a contributing cause of cholera

Understanding *The Abductive Process of Scientific Inquiry* shows why this was unfortunate, but not irrational

- Not *necessarily* a case of "smart people cling[ing] to an outlandishly incorrect idea despite substantial evidence to the contrary" (Johnson)

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Abductive Process of Scientific Inquiry

Scientific inquiry and the growth of knowledge is an ambiguous, uncertain, complex process.

- Not progressing mechanically, difficult to quantify
- A complicated and dynamic interplay between data, theory, and testing

We call upon the work of two (three) philosophers

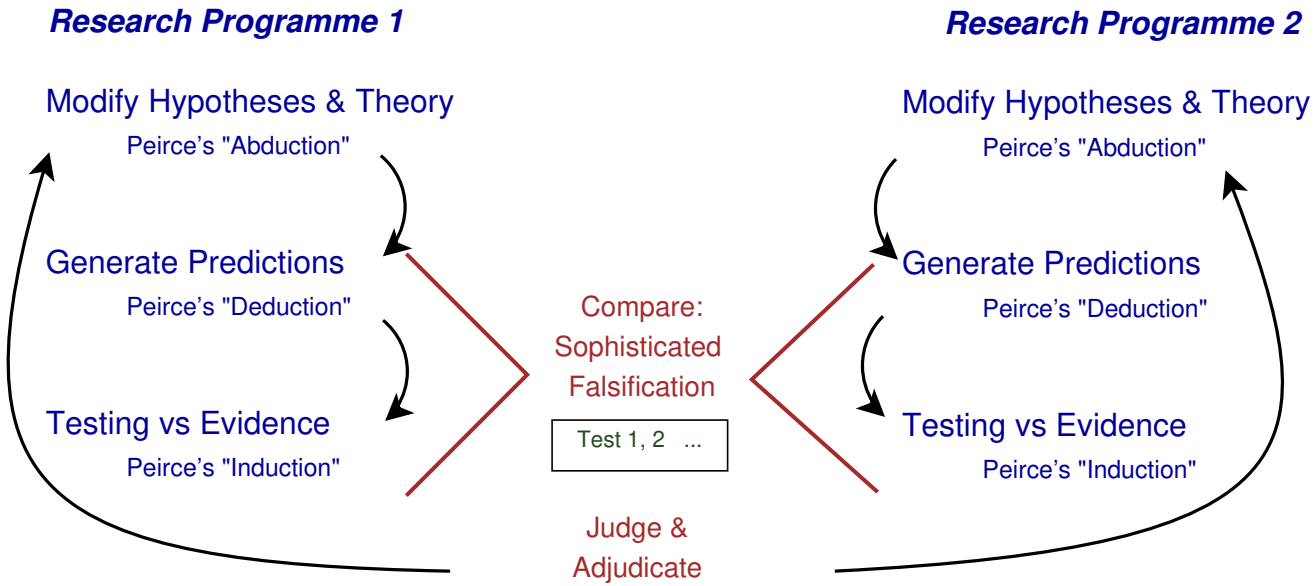
- Charles Sanders Peirce (1839-1914), "father of pragmatism", proposed "path inquiry"
  - Three stages of scientific inquiry: *Abduction*, *Deduction*, *Induction*
- Imre Lakatos (1922-1974), philosopher of science, student of Karl Popper
  - "Unit of appraisal" for scientific inquiry is a *research programme* – collection of theories and hypotheses with structure
  - *Sophisticated Falsification* for comparing and deciding between programmes

Abductive Process of Scientific Inquiry

Peirce's 3 stages of Inquiry

1. Develop & modify theories (abudction)
2. Generate predictions from theories (deduction)
3. Test predictions vs evidence (induction)

On-going process



Research Programme as unit of analysis from Lakatos. We also need a *criterion* for choosing between theories and programmes – when is one theory thrown out and supplanted by another

- Something more than Thomas Kuhn's psycho-social *Scientific Revolutions*
- Popper's proposal of *falsification* seems like the answer, but it does not work – the how and why holds the answer to airborne theories' adoption of water

Falsification: Dogmatic, Naive, Sophisticated

Karl Popper (1902-1994) introduced idea of *Falsification* and *Falsifiability*

- Trying to solve a problem: We cannot *Verify* a scientific theory. But surely we can *Falsify* it?
- Built a philosophy of science based around theories that could be falsified or refuted

Turns out Falsification is not so simple

- A contradiction implies some particular *hypothesis* or theory under scrutiny, surrounded by (and tested using) accepted facts and theories
- But any "accepted" fact or theory is only accepted provisionally, always subject to revision (Peirce recognized this)
- Instead of rejecting the *hypothesis*, we may revise the "facts" or "accepted theories" to make the contradiction go away.
- Essence of the Duhem-Quine thesis

Lakatos's *Research Programmes* and *Sophisticated Falsification*

Scientific Research Programme as the fundamental unit we work with:

- Not an isolated hypothesis, but a developing series of theories
- *Hard core* – not (generally) subject to revision or refutation
- *Auxiliary belt* – translate core to world of observations, readily added to, revised

Sophisticated Falsification: a scientific theory T is falsified if and only if another theory T' has been proposed for which:

1. T' has excess empirical content (predicts novel facts, not predicted by T)
2. T' explains previous success of T (unrefuted content of T is included)
3. Some of the excess content of T' is corroborated

Not really *falsification* at all, but a ***criterion for supplanting***

Progressive versus *Degenerating* Programmes

Adjustments and additions to hypotheses and theories (generally the auxiliary belt) may be

- ***Progressive***: generate *new* predictions and new facts
- ***Degenerating***: remove and account for anomalies, but do not generate new facts or theoretical insights

This distinction is the essence of Lakatos's methodology, essence of supplanting an old theory with new

Lakatos's conjecture (and I do think we need to treat it as a conjecture) is that *Progressive* programmes lead to increases in knowledge, *Degenerating* programmes do not.

- Foundational problems in defining and talking about *knowledge* and *truth* mean that I think this is a conjecture. But a very useful one.

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Cholera 1849-1866 as an Example of the Abductive Process

Apply ideas of Peirce and Lakatos to developments 1849-1866

1849, Snow's abductive leap

- Surprising fact *C* (anomaly): airborne cholera seems sometimes contagious, sometimes not
- If hypothesis *A* (intestinal, fecal-oral transmission) were true, *C* would be a matter of course

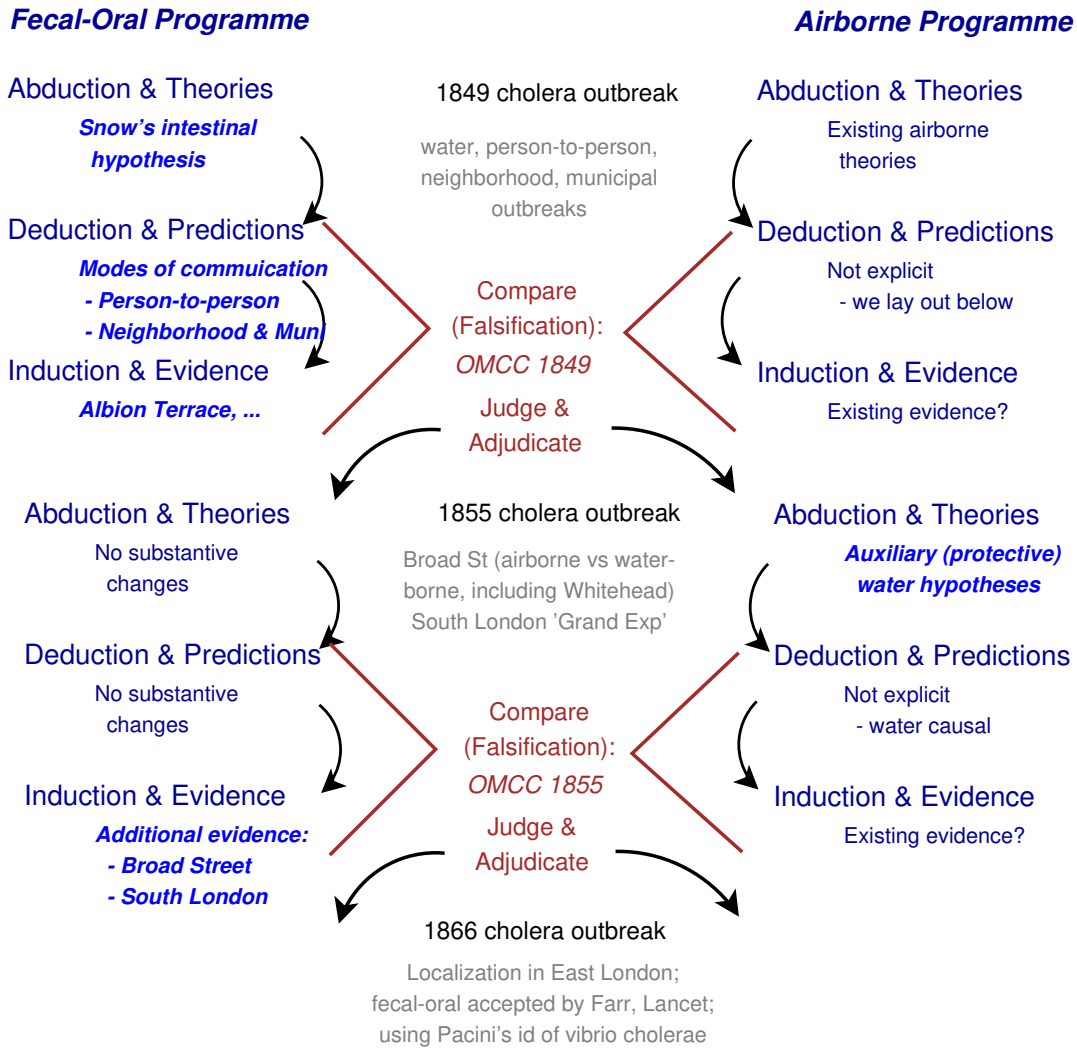
OMCC: Generating predictions, testing against evidence

- Effort at *Falsification* – limited success

Airborne response

- New auxiliary hypotheses: water as causal, water transmission

1855: new evidence, new round
1866: wider acceptance, new evidence



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1855 Comparison and Falsification

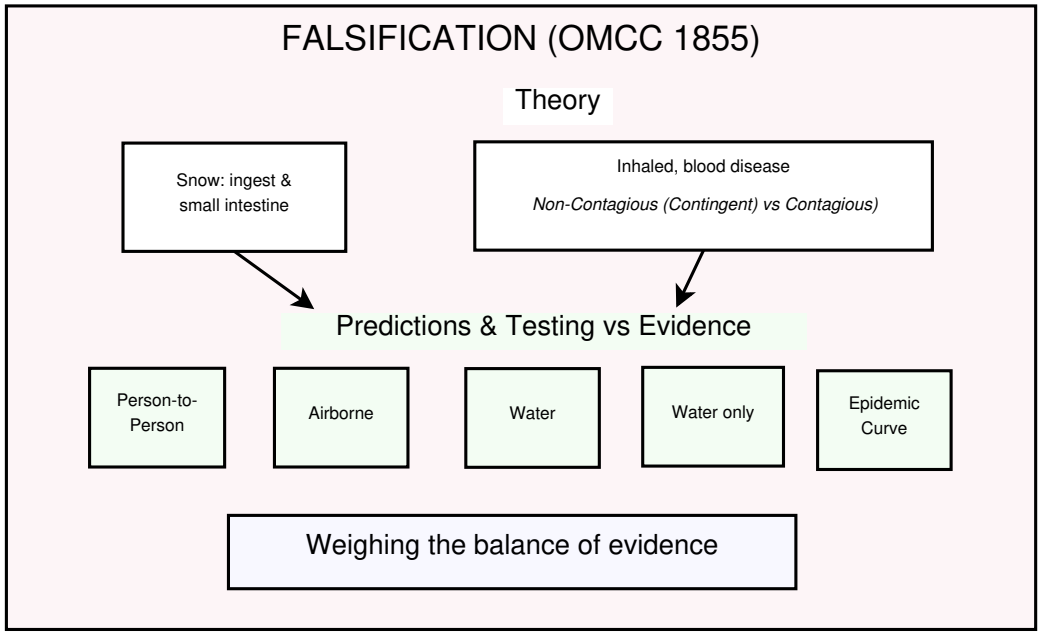
We view Snow's 1855 *On the mode of communication of cholera* as an extended effort at falsification – demonstrating the superiority of the fecal-oral to alternative theories

Steps for falsification:

1. Lay out competing theories
2. Develop predictions from theories
3. Compare predictions versus evidence

Echos approach of Katz & Singer

- Assemble broad range of disparate evidence, varying forms and quality



Here, hypothesis testing in a Neyman-Rubin potential outcome framework takes the role of strengthening the weight of (some) evidence

- For example, by reliably showing that water is *causal*, and observed association is not spurious (causation and not correlation)

Cholera Theories and Predictions

Major predictions (more complete in paper)
Important comments:

- Value of a prediction / observation – discriminating between theories – requires divergent predictions
- *Water* has low value – theories predict the same
- *Contagion* high value – theories predict different patterns (e.g. doctors attending patients)
- *Epidemic Curve* are new predictions from fecal-oral, no prediction from airborne

	Prediction/Observation	Predict? Fecal	Air	Value
	PERSON-TO-PERSON CONTAGION			
2a	***Airborne contagion*** for those sharing airspace	N	Y	**High**
2b	***Person-to-person contagion*** sharing food, clothing	Y	N	**High**
	GENERAL CHARACTERISTICS			
4	***Transmission by Air***	N	Y/N	Medium
5b	***Water is causal***	Y	Y	Low
5c-f	***No Other Factors Causal***	Y	N	Medium
	EPIDEMIC CURVE			
8	***Explosive neighborhood outbreaks***	Y	N	**High**
9	***Municipal mortality differs early vs late***	Y	N	**High**

Each row presents a prediction about observed patterns of mortality. "Yes" or "No" in a column (and color) indicates whether the theory in the column predicts the observation, or the opposite. This table does not compare predictions versus evidence.

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Summarizing Predictions vs Evidence

"Y/P" indicates support, due to protective auxiliary hypothesis

Water as Causal

- No use for distinguishing between theories
- Fecal-oral and airborne predict water as a cause

Transmission by Air

- Broad St: examples of residents sharing air but not dying (workhouse, brewery)
- Also those sharing water & not air and dying (widow in Hampstead)
- Evidence not transmitted via air, no positive evidence
- Airborne protected via auxiliary hypothesis

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Summarizing Predictions vs Evidence

Other Factors not important

- New prediction by fecal-oral
- (Weakly) corroborated in 1856

Epidemic Curve

- Neighborhood: localized outbreaks, explosive in growth, quickly tailing off
- Albion Terrace, Horsleydown, others
- Municipal: at beginning (infection mainly municipal water) large ratio of mortality rates. Later, normal propagation, less difference

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Summarizing Predictions vs Evidence

Lakatos's *Sophisticated Falsification* requires:

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2. T' explains previous success of T
3. Some of the excess content of T' is corroborated

Fecal-oral satisfies all: new facts ("no other factors", "epidemic curve", even "contagion") corroborated

- For airborne, auxiliary water is *degenerating* (ad hoc) hypothesis – produces no new facts

	Prediction/Observation	Support? Fecal	Air	Value
	PERSON-TO-PERSON CONTAGION			
2a	***Airborne contagion*** for those sharing airspace	Y	N	**High**
2b	***Person-to-person contagion*** sharing food, clothing	Y	N	**High**
	GENERAL CHARACTERISTICS			
4	***Transmission by Air***	Y	Y/P	Medium
5b	***Water is causal***	Y	Y/P	Low
5c-f	***No Other Factors Causal***	Y	N	Medium
	EPIDEMIC CURVE			
8	***Explosive neighborhood outbreaks***	Y	N	**High**
9	***Municipal mortality differs early vs late***	Y	N	**High**

Each row presents a prediction about observed patterns of mortality. "Yes" or "No" in a column (and color) indicates whether the theory in the column is supported by (matches) the observation

Summarizing Predictions vs Evidence

Strong argument that fecal-oral was the better theory

- Predicted novel facts, that were corroborated

But still reasons to be skeptical about fecal-oral

- *Mechanism* not well understood (or rather not well-recognized) – could not test for and trace "cholera poison"
- By 1866, Farr had visited and recognized Pacini's identification of *vibrio cholerae*

Outline

1 Overview: John Snow and the Story of Cholera

2 Potential Outcome and "Causal Water" in 1849

Standard Story: Causal Water – Difference-in-Differences and Randomization

Airborne Theories Adopt "Causal Water"

3 Abductive Process of Scientific Inquiry and Snow's Theory 1849-66

Abductive Process: Pierce's 3 Stages and Lakatos's *research programmes*

Cholera 1849-1866 as an Example of the Abductive Process

4 Falsification and Comparing Theories in 1855

Cholera Theories and Predictions

Comparing Predictions vs Evidence

5 Conclusion

1866 and Wider Acceptance

Cholera struck London again in 1866

- Limited to East London – supplied by East London Water Company

Some (William Farr in particular) now subscribed to fecal-oral theory

- Efforts, ultimately successful, to demonstrate the East London Water Company supplied contaminated water (and broke laws)

Reports to Privy Council and Parliament supported fecal oral

- Strong statistical evidence, little chemical or biological evidence (testing for contaminated water)
- Supported Snow. Quoted (and used) Pacini's identification of cholera baceteria

Remaining Puzzle: why was it not until the 1880s (and Robert Koch) that the bacterium was widely recognized?

- Maybe if microscopists in 1866 had identified in East London water?

Outline

6 Details on South London Evidence for Causal Water

Overview

Snow's Analysis

"Grand Experiment" – Water Supply Changes

Two water companies served south London – Southwark & Vauxhall Co and Lambeth Co. – 486,936 customers, 300,000 **intimately mixed**

- In 1830s & 1840s companies competed for customers, often on same street
  In many cases a single house has a supply different from that on either side. Each company supplies both rich and poor, both large houses and small; there is no difference in the condition or occupation of the persons receiving the water of the different companies. (Snow 1855 p 75)

1849 epidemic

- Both companies drew water from low in the Thames – near Vauxhall bridge

1852

- Lambeth Company moved source to Thames Ditton (upstream of London)
- In response to Act of Parliament, requiring move (by 1855)

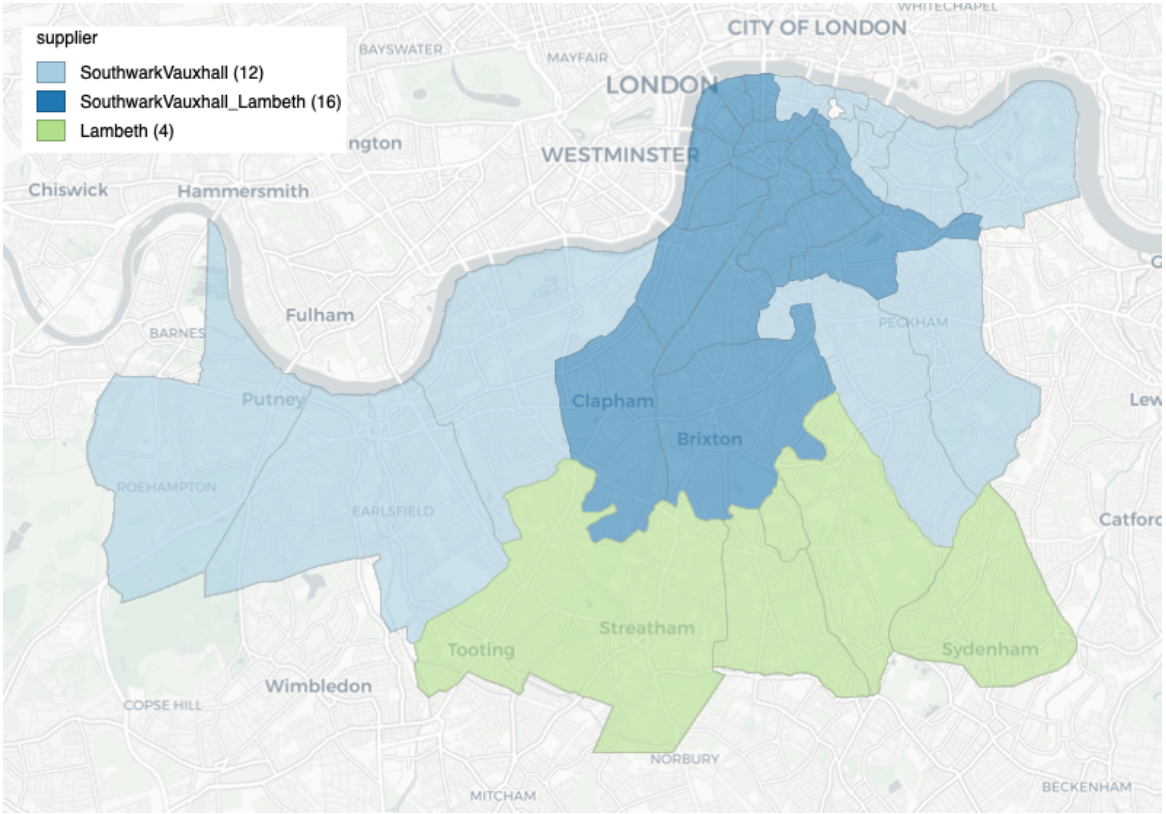
1854 epidemic

- Southwark & Vauxhall Co supplied dirty water
- Lambeth Co supplied cleaner water

32 Subdistricts, 12 S&V only, 16 joint, 4 Lambeth

Registration Districts & Sub-Districts – Need to keep straight

- Deaths collected weekly by Registrar-General, by District & Subdistrict
- In this region of South London, 32 sub-districts
- Some supplied S&V only, others joint
- DiD: compare "S&V only" vs "joint"
- Mixing & randomization: ideally, compare within "joint"



- "First 12" (light blue) – Southwark & Vauxhall Water Co only – dirty water 1849 & 1854
- "Next 16" Mixed or Joint (dark blue) – Southwark & Vauxhall Co *and* Lambeth Water Co – 1849 dirty water, 1854 part dirty (S&V) & part clean (Lambeth)
- "Final 4" – Lambeth Water Co only – not relevant, not supplied in 1849

Deaths: Combined (All Suppliers) vs Direct (By Supplier)

Data available in 1855

- Deaths (combined all suppliers) 1849 & 1854, full epidemic
- Population (combined all suppliers)
- Deaths by supplier, first 7 weeks of epidemic (collected by Snow)

Data available in 1856 (originally published by Simon)

- Population by supplier (only S&V shown here)

						1854, first 7 wks		
	subdistricts	Deaths 1849	Deaths 1854	Supplier	Population 1851	Deaths S&V	Deaths Lam	Pop S&V
1	St. Saviour	283	371	SV	19,709	115	0	16,337
2	St. Olave	157	161	SV	8,015	43	0	8,745
13	Christchurch	256	113	SV & Lambeth	16,022	11	13	2,915
14	Kent Road	267	174	SV & Lambeth	18,126	52	5	12,630
29	Norwood	2	10	Lambeth	3,977	0	2	0
	TOTAL	6,328	5,042		486,936	1,263	98	266,516

Combined (all suppliers)	Direct (by supplier)
$D_{subdist} = D_{S\&V} + D_{Lam} + D_{Other}$	$\{D_{S\&V}, D_{Lam}, D_{Other}\}$

6 Details on South London Evidence for Causal Water

Overview

Snow's Analysis

Snow's Analysis – 2 Approaches

Mixing or quasi-random direct comparison

- Snow determined supplier – by bill or chloride test
- Visited all houses (deaths) for 7 weeks ending Aug 26

Diff-in-Diffs comparison of combined (all suppliers) mortality rates

- For each subdistrict, observe combined deaths all suppliers
- Compare 1849 vs 1854 and Treated (clean) vs untreated (dirty) subdistricts

Snow Modern in View of Mixing (Randomization)

Recognized that mixing (randomization) would average out differences

> *As there is no difference whatever, either in the houses or the people receiving the supply of the two Water Companies, or in any of the physical conditions with which they are surrounded, it is obvious that no experiment could have been devised which would' more thoroughly test the effect of water supply on the progress of cholera than this. (1855 p. 75)*

Cited as first instance of Randomization and Instrumental Variables (Greene 2018, also Deaton, others)

Comparison of Mixed or Randomized Population

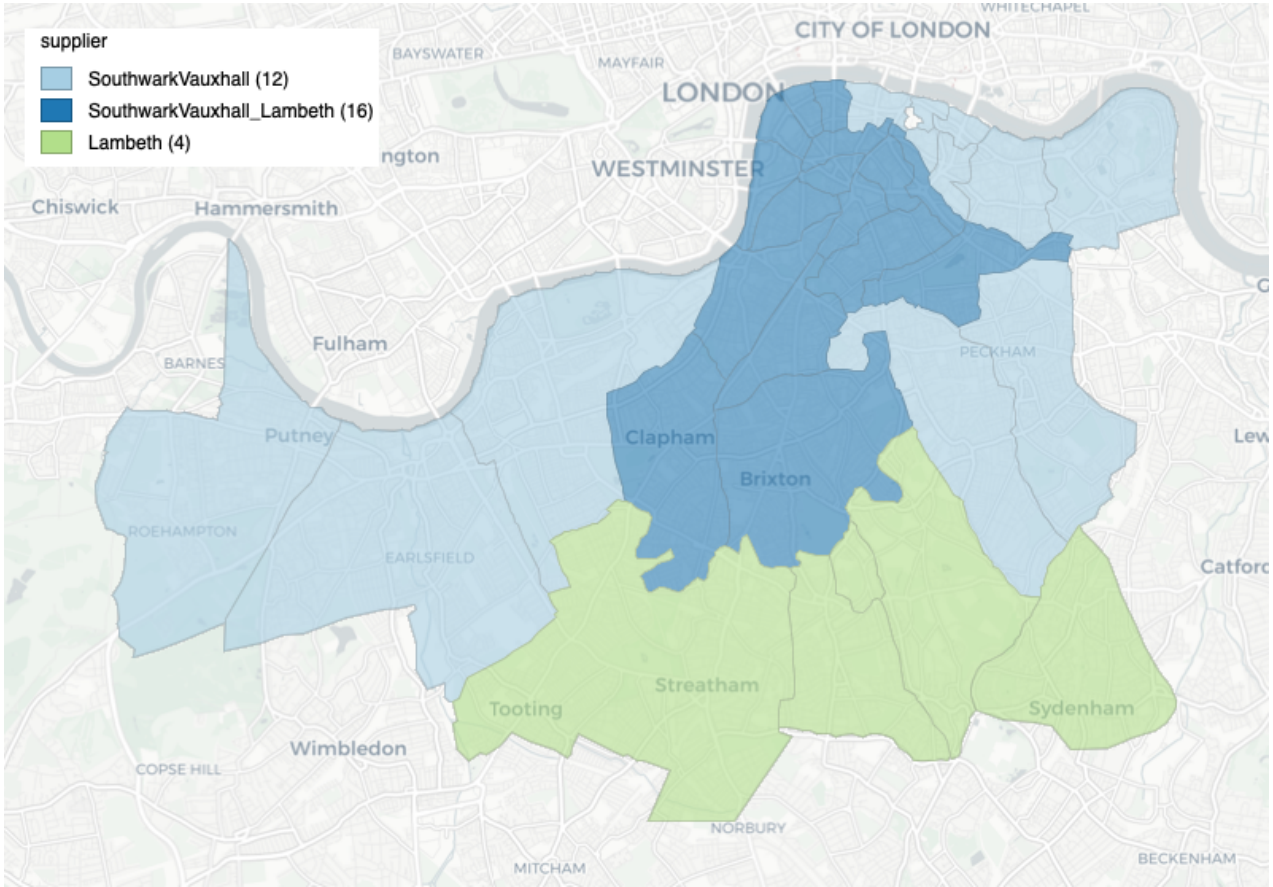
Table: Houses, Deaths, and Mortality Rates per 10,000 Households, First Seven Weeks of 1854 Cholera Epidemic – Table IX

Water Supplier	Number of houses	Deaths from Cholera	Deaths in each 10,000 houses
Southwark & Vauxhall Co supply	40,046	1,263	315.4
Lambeth Co supply	26,107	98	37.5
Rest of London	256,423	1,422	59
Ratio Effect: Southwark & Vauxhall vs Lambeth			8.40

Note that this corrects a rounding error in the "Deaths in each 10,000 houses" for Lambeth in Snow's original table

- Found LARGE Lambeth effect
- But suffered from potential confounding – includes **all** subdistricts

Problem: Snow's Mixing Comparison Uses *All* Subdistricts



- Snow wanted to limit analysis to Joint (Mixed) subdistricts – could not
- Population (houses) by supplier for overall region only
- Potential for confounding (bias if S&V-only subdistricts different than joint)

Second Approach – DiD – Before v After, Treated v Control

Comparing the S&V-only subdistricts vs the Jointly-supplied subdistricts

- Interestingly, Snow did not convert deaths to rates – missed an opportunity
- Large treatment effect, but need to evaluate statistical significance

Mortality Rates 1849 & 1854, Summary Snow 1855 Table XII

	1849 Deaths per 10,000	1854 Deaths per 10,000	Ratio 1849 - 1854
Always Dirty – Southwark & Vauxhall Water Company Only ("First 12" subdistricts)	134.9 dirty, S&V only	146.6 dirty, S&V only	0.92 diff in time
Dirty / Clean – Joint Southwark & Vauxhall and Lambeth Companies ("Next 16" subdistricts)	130.1 dirty, joint	84.9 (partial) clean	1.53 diff in time & treatment
Ratio: Next 16 less First 12	0.96 diff in region	1.73 diff in region & treatment	1.67 (partial) treatment

Problem: treatment effect only marginally significant

DiD as Regression

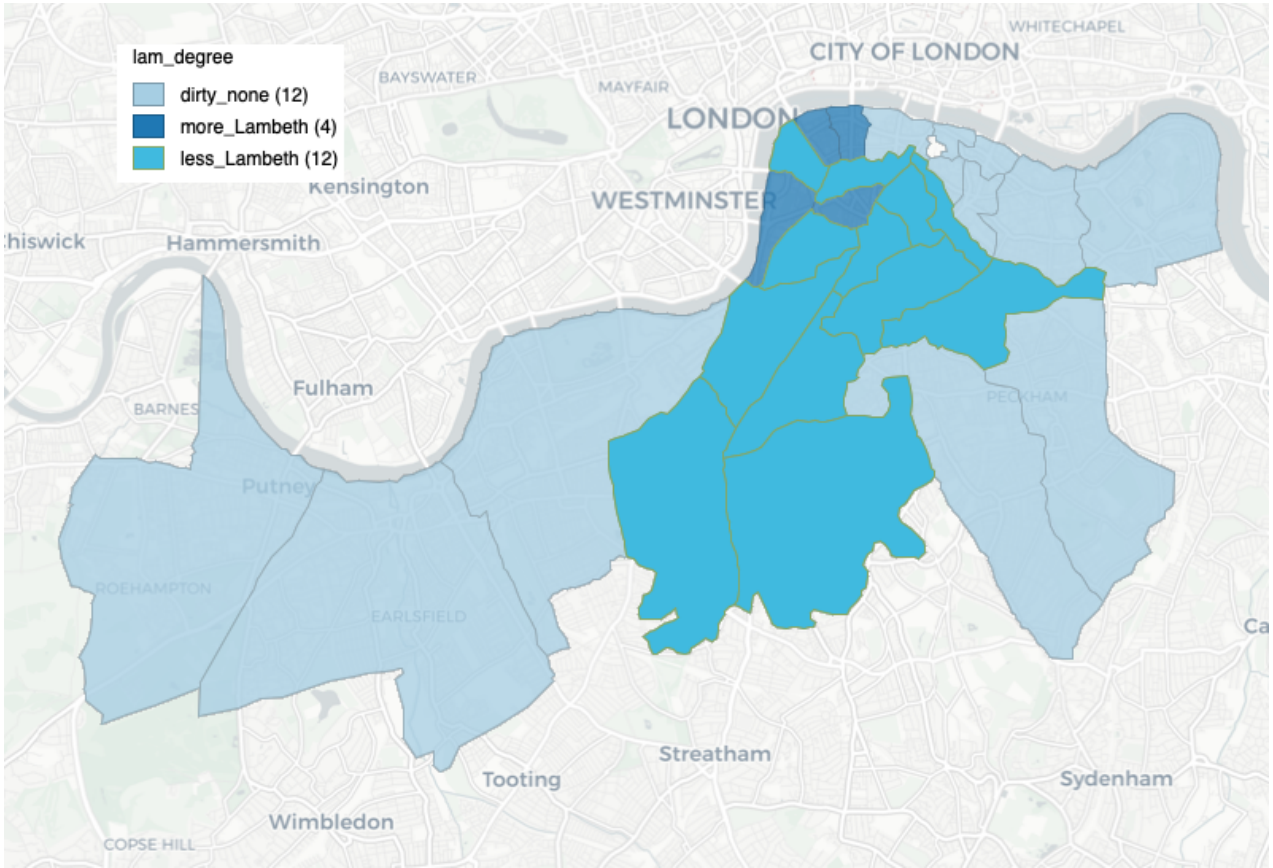
$$\ln\left(Rate_{subdist,yr}\right) = \ln\left(count_{subdist,yr}/population_{subdist,yr}\right) = \hat{\mu} + \hat{\delta}_{54} \cdot I_{yr=1854} + \hat{\gamma}_J \cdot I_{subdist=joint} + \hat{\beta} \cdot I_{subdist=joint} \cdot I_{yr=1854} + \varepsilon_{s,y}$$

Region or Sub-Districts – Supplied by	1849 Death Rate (log)	1854 Death Rate (log)	Diff 1854 less 1849
First 12 – Southwark Only	μ	$\mu + \delta_{54}$	δ_{54}
Next 16 – Joint Southwark and Lambeth	$\mu + \gamma_J$	$\mu + \delta_{54} + \beta + \gamma_J$	$\delta_{54} + \beta$
Diff Joint less Southwark	γ_J	$\beta + \gamma_J$	β

Regression framework allows us to

- Use subdistrict detail, and additional regressors (if available)
- Test for statistical significance (both for finite population and "within-sample" variation)
- Extend the DiD framework to continuous treatment and actual-vs-predicted

Snow Highlighted Difference in "Lambeth Degree"



- Four subdistricts where "the supply of the Lambeth Water Company is more general than elsewhere"

Snow Highlighted Difference in "Lambeth Degree"

	1849 Deaths per 10,000	1854 Deaths per 10,000	Ratio 1849 - 1854
Always Dirty – Southwark & Vauxhall Water Company Only ("First 12" subdistricts)	134.9 dirty, S&V only	146.6 dirty, S&V only	0.92 diff in time
Dirty / Clean – "More Lambeth" in Joint (4 subdistricts)	138.8 dirty, more	47.2 more clean	2.94 time & more
Dirty / Clean – "Less Lambeth" in Joint (12 subdistricts)	127.6 dirty, less	95.6 less clean	1.34 time & less
Ratio: "More Lambeth" vs Dirty	0.97 diff in region	3.11 region & more	3.20 more treatment
Ratio: "Less Lambeth" vs Dirty	1.06 diff in region	1.53 region & less	1.45 less treatment

Larger effect for "More Lambeth"

- Now, treatment effect is highly significant (see below)