Causal AI for Automated Root Cause Analysis (with applications in Public Health)

Root cause analysis (RCA) is a problem-solving approach aimed at identifying the fundamental factors that give rise to observed problems or anomalies. In the public health domain, RCA is crucial for understanding why unexpected epidemiological events occur, for example discovering why a disease outbreak emerged in a particular region or why incidence rates suddenly spiked or dropped.

Several factors make this an opportune time to pursue automated, data-driven RCA in Brazil. First, Brazil's Unified Health System (Sistema Único de Saúde, the SUS) and other public institutions have invested heavily in health information systems, resulting in abundant high-quality data. Large-scale databases from SUS (e.g., hospital admissions, surveillance notifications, mortality records), socio-demographic data from the Brazilian Institute of Geography and Statistics (IBGE), and environmental data such as climate records from the National Institute of Meteorology (INMET) are publicly available. These datasets enable epidemiologists to observe patterns across time, location, and population with granular detail. For example, recent digital health initiatives in Brazil have successfully integrated data from SINAN (the national notifiable diseases system), IBGE, and INMET to predict dengue fever case counts in different municipalities. Such initiatives demonstrate the feasibility of linking health outcomes with socio-environmental factors, and they highlight the potential for more sophisticated analyses like RCA using these rich data sources. Moreover, the development of modern epidemiology in Brazil, exemplified by national programs for health data integration and analysis, has emphasized the use of evidence-based approaches to inform policy.

A project that applies cutting-edge causal AI to Brazilian public health data aligns perfectly with this trajectory, contributing to a "health intelligence" capacity that can uncover *why* adverse health events happen and how to address them. This project aims to automate RCA for epidemiological phenomena by harnessing causal inference methods. In contrast to purely correlational data mining, we will employ formal causal models (e.g., DAGs encoding hypothesized causal links among variables) and counterfactual reasoning to identify the causes of public health events. In practice, this means using techniques that can compute the likely effect of potential causes (or their removal) on outcomes of interest. Structural Causal Models will be the backbone, allowing us to articulate assumptions about how various factors (e.g., rainfall, mosquito abundance, sanitation infrastructure, human behavior) interact to produce an outcome like a disease outbreak. The exact analytical techniques will be finalized after an initial data exploration phase; however, our *working hypothesis* is that recent advances in causal machine learning can be leveraged for this purpose.

In particular, we plan to investigate the use of Deep Twin Networks, a deep-learning-based approach for counterfactual inference, to compute probabilities of causation in complex epidemiological data. Deep Twin Networks are neural architectures that learn the underlying causal mechanisms from data and enable estimation of counterfactual outcomes. By training such models on Brazilian health data, we expect to estimate probabilities of causation that quantify each candidate factor's causal contribution to an epidemiological event.

A formal framework for *probabilities of causation* will guide the RCA in this project. Following Pearl's definitions, we consider measures like the *Probability of Necessity (PN)* and *Probability of Sufficiency (PS)*, which are rooted in counterfactual logic. For a given factor *X* (e.g., an environmental exposure) and outcome *Y* (e.g., occurrence of an outbreak), PN asks: "to what extent was *X* necessary for *Y* to happen?". Conversely, PS asks: "to what extent is *X* alone sufficient to produce *Y*?". Combined with the probability of necessity *and* sufficiency (PNS), these metrics provide a quantitative ranking of plausible causes.

In an epidemiological context, such metrics could, for instance, help distinguish whether a surge in respiratory disease is *necessarily* tied to an environmental trigger (like a pollution spike) or if that trigger alone would be *sufficient* to cause the surge. Computing these probabilities in practice, however, is challenging – especially with categorical or continuous variables and in the presence of unobserved confounders (the typical scenario in population health data, which we call quasi-Markovian models). The literature shows that when not all confounders are observed, one often cannot identify exact causal probabilities, and must instead derive bounds on them. We will address this challenge by adapting techniques from recent research on quasi-Markovian causal models. In particular, we draw inspiration from *"Probabilities of Causation and Root Cause Analysis with Quasi-Markovian Models,"* which outlines how to handle hidden confounding in RCA by computing bounded estimates of PN, PS, and related quantities. By integrating these ideas with the Deep Twin Networks approach (which enforces certain functional constraints to ensure counterfactuals are well-behaved even in categorical data), we aim to create a robust method capable of performing RCA on epidemiological data that include mixed variable types and latent factors.

In summary, the project's approach marries causal inference (DAG-based reasoning and Pearl's counterfactual definitions) with modern AI techniques (deep learning models for counterfactual prediction), to build an automated RCA system for public health. This aligns with the emerging paradigm of Causal AI, which goes beyond predictive analytics to provide explanatory insights grounded in causality theory.

Objectives

General Objective: Develop and validate a novel *causal AI framework* for automated root cause analysis of epidemiological phenomena, with a focus in Brazil, in order to identify the underlying causes of outbreaks and anomalous public health events using multi-source public data and cutting-edge causal inference methods.

Specific Objectives:

1. **Data Acquisition & Integration**: Identify, obtain, and preprocess relevant public health datasets from Brazil (e.g. disease incidence and surveillance data from SUS, demographic and socio-economic indicators from IBGE, meteorological data from INMET). This objective includes building a unified data repository and ensuring data quality, so that epidemiological indicators can be analyzed alongside potential causal factors at various scales.

2. **Method Development – Causal Discovery and Inference**: Develop or adapt computational methods for discovering local causal relationships and quantifying causal effects in the data. This includes exploring causal discovery algorithms to suggest plausible DAG structures from data, and implementing causal inference techniques to compute counterfactual quantities. A starting point will be to implement the Deep Twin Networks approach for estimating counterfactual outcomes and probabilities of causation, and then refine this approach for epidemiological contexts (e.g., by incorporating domain knowledge into the DAG structure, or by extending the method to handle temporal dynamics and spatial correlations common in epidemiology). We will also extend existing formulations (currently often limited to binary variables) to accommodate categorical and continuous covariates, also common in public health data.

3. **Application to Case Studies (Validation)**: Apply the developed RCA framework to real epidemiological case studies in Brazil. Potential case studies might include: investigating the root causes of a localized dengue fever outbreak, identifying drivers of a sudden rise in respiratory illness hospitalizations in a region, or explaining an unusual drop in incidence of a disease (for instance, to see if it correlates with an intervention or environmental change). Model findings will be validated against expert knowledge and historical evidence (where available) to assess plausibility. The outcome of this objective will be a set of epidemiological insights and lessons learned about the strengths and limitations of the method in practice.

4. **Framework Evaluation and Comparison**: Rigorously evaluate the proposed RCA framework's performance and utility. This entails comparing our causal-inference-based RCA results with traditional analytical approaches

used in epidemiology. For instance, if traditional analysis identified multiple correlates of an outbreak, does our approach pinpoint a smaller set of true causes with higher confidence? We will use quantitative metrics (where possible) for evaluation, such as accuracy of predicting the impact of interventions (removing a purported cause) in retrospective analysis, as well as qualitative input from domain experts on the actionability of the results. This objective will demonstrate the value added by formal causal methods. It will also highlight any gaps (e.g., data limitations or methodological challenges) that need to be addressed in future work.

Through these objectives, the thesis will progress from data gathering, to method development, to real-world application and critical evaluation, ensuring that the end product is both scientifically sound and relevant for public health decision-making. This project stands at the intersection of epidemiology, data science and artificial intelligence, promising contributions to each.

Analogous efforts in other fields have shown promise, and these efforts underscore a broader shift toward *causality-aware* analytics. By bringing similar innovations to public health, our work ensures that epidemiology keeps pace with advances in data science and artificial intelligence.

Roadmap for Next Months

1. **Literature Review:** Comprehensive review of causal inference frameworks, RCA methodologies, and Brazilian epidemiological studies.
2. **Data Exploration:** Obtain and explore SUS, IBGE, and INMET datasets, selecting initial case studies based on data quality and public health relevance. The main goal is to obtain datasets such as notified cases of selected diseases, hospitalization records, population demographics, and weather measurements for regions of interest.
3. **Expert Consultations:** Engage with experts in epidemiology and public health (for example, academic researchers, epidemiologists from Brazilian health institutes, or data analysts at DATASUS) to refine the research and ensure practical relevance.
4. **Feasibility Studies:** Conduct initial tests of candidate methods (including Deep Twin Networks) on selected datasets to evaluate practicality and identify potential methodological refinements.
5. **Preliminary Modeling:** Develop initial causal models and prototype RCA analyses, forming the basis for thesis structure.
6. **Qualification Preparation:** Consolidate findings and methodologies into a formal qualification report, demonstrating project viability and readiness for advanced research phases.

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