

CAUSAL INFERENCE AND MACHINE LEARNING

(or a crash course on causality for ML practitioners)

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About this talk

The relationship between causality and artificial intelligence can be seen from two points of view: how causality can help solve some of the current problems of AI and how causal inference can leverage machine learning techniques. In this course we will review the two points of view with special emphasis on examples and practical cases.

- 01 • **Introduction**
Observational and Interventional Distributions. Causal Thinking.
- 02 • **Causal Graphs**
Do Calculus

- 03 • **Estimands**
From Metalearners to Counterfactuals
- 04 • **Causal Machine Learning**
Supervised and Reinforcement Learning
- 05 • **Practical Causal Inference**
Example

About the course

The relationship between causality and artificial intelligence can be seen from two points of view: how causality can help solve some of the current problems of AI and how causal inference can leverage machine learning techniques. In this course we will review the two points of view with special emphasis on examples and practical cases.

The screenshot shows the GitHub repository page for 'EBISS2023'. The repository has 1 branch and 0 tags. The README file contains the following text:

```
EBISS2023: Causal Artificial Intelligence

The scientific method aims at the discovery and modeling of causal relationships from data. It is not enough to know that smoking and cancer are correlated; the important thing is to know that if we start smoking or stop smoking, it will change our chance of getting cancer. Artificial Intelligence and Machine learning as it exists today does not take causation into account and instead make predictions based on statistical associations. This can give rise to problems when they are used in environments in which the associations used are not necessarily fulfilled or when such models are used for decision making. This picture has begun to change with recent advances in techniques for causal inference, which make it possible (under certain circumstances) to measure causal relationships from observational and experimental data and, in general, to make formal reasoning about cause and effect. As we will discuss in the talk, the convergence between machine learning and causal inference opens the door to answering questions relevant to many AI tasks.
```

The repository has 2 commits, the latest being 'algoritmes Update README.md' by b2e2313 8 minutes ago. There is also a file 'README.md' with the same update information.

On the right side, there is an 'About' section with the message: 'No description, website, or topics provided.' It also shows the repository's activity: 0 stars, 1 watching, 0 forks, and 0 releases published. A link to 'Report repository' is available.

<https://github.com/DataScienceUB/EBISS2023>

Introduction

Observational and Interventional Distributions.
Causal Thinking.

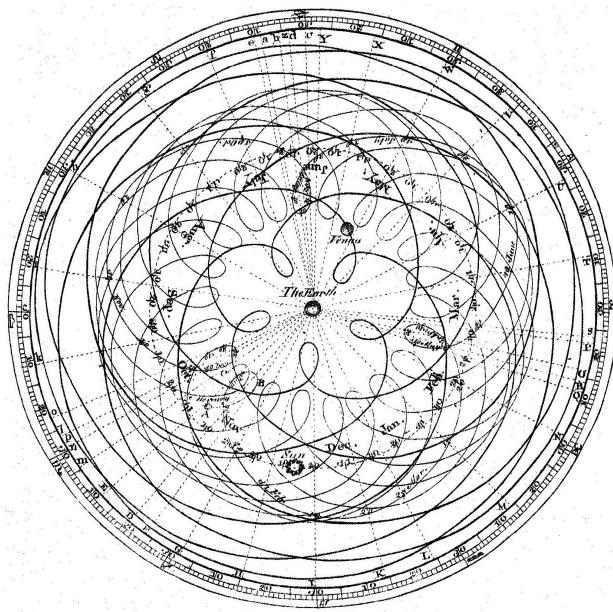
Jordi Vitrià
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Can we predict what we see in the sky?

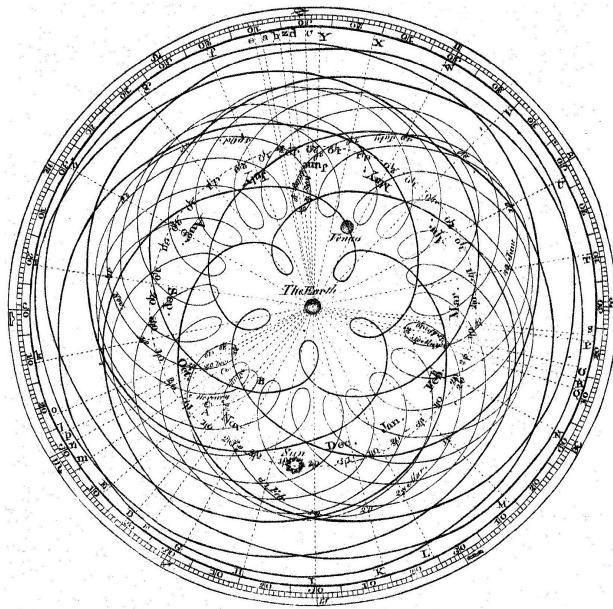
ML Mindset = Gathering data + Building a model

Predicting observations vs predicting interventions

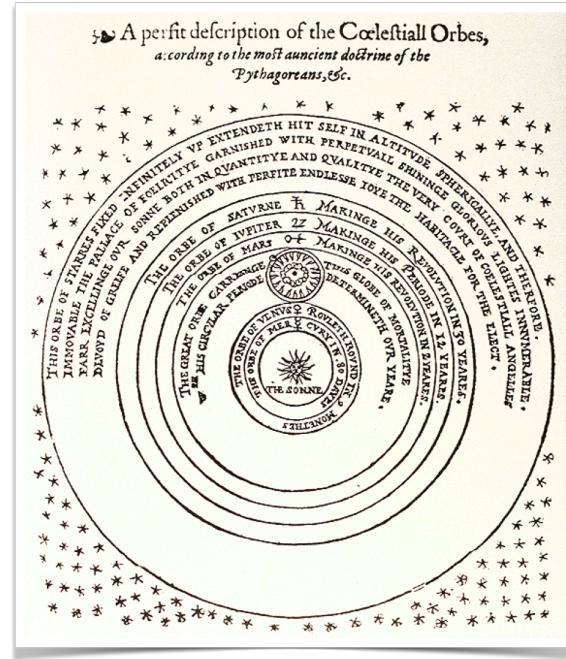


Ptolemaic model (circular orbits, geocentric)
100 AD

Predicting observations vs predicting interventions



Ptolemaic model (circular orbits, geocentric)
100 AD



Copernican model (heliocentric, harmonious = fewer causes)
1543 AD

Predicting observations vs predicting interventions

Ptolomeus and Copernicus build models with **high predictive power.** (Statistical/ML Mindset)



But they both were “**false**”!
(Causal/Scientific Mindset)



Predicting observations vs predicting interventions



- Predictions were not false in the “predictive” (Statistical/ML) sense, but in the “**interventional**” (scientific/causal) sense.
- What about aliens destroying (**intervening**) a planet instantly?

Predicting observations vs predicting interventions

Statistical inference and machine learning models are designed to predict **observations** (observational data) in **stable** environments.

They are based on analyzing data to answer **associative questions**.

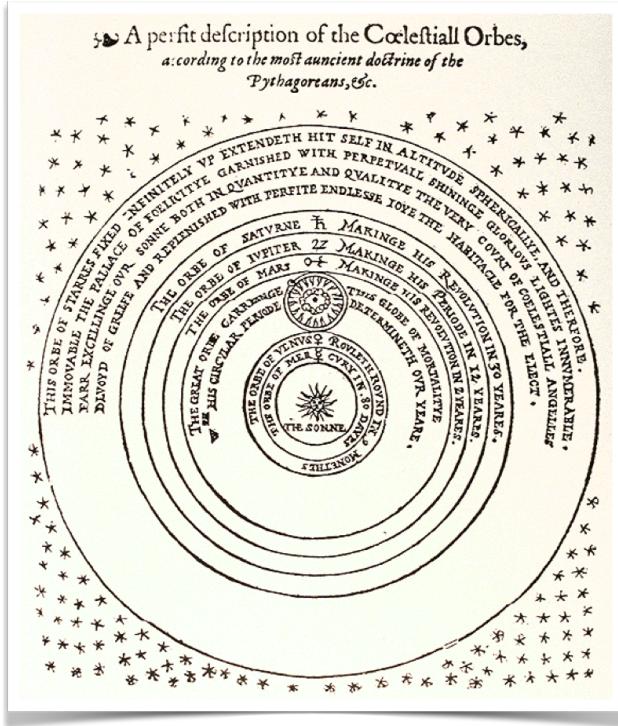
Predicting observations vs predicting interventions



the weather
What can I say about Y given
that I have observed X ?

umbrellas
What can I say about X given
that I have observed Y ?

Predicting observations vs predicting interventions



Modern ML models are very good at discovering and using associative structures in (X, Y) for predicting the value of Y in **pure observational settings**.

But predictive models can be accurate without being “correct” in **interventional settings**.

AI sucks...
or how CI can help ML

AI sucks...

AI based **high stake decisions** (risk scoring in home credit)

Bogdan Kulynych @hiddenmarkov · 19 h
"Number of elevators in the building where the client *currently lives*" ...
1 reply | 1 retweet | 8 likes

Use of spurious correlations.

Bogdan Kulynych @hiddenmarkov
Looking through a popular public dataset for risk scoring in home credit from a real home credit company, and some of the features included there are absolutely wild:
Tradueix el tuit
3:28 p. m. · 12 d'oct. de 2021 · Twitter Web App
14 Retuits 3 Tuits amb cita 43 Agradaments

Tuita una resposta Respon

Bogdan Kulynych @hiddenmarkov · 19 h
En resposta a @hiddenmarkov
"Who was accompanying client when he was applying for the loan?"
(Unaccompanied, spouse, partner, group of people)
1 reply | 1 retweet | 6 likes

Bogdan Kulynych @hiddenmarkov · 19 h
"On which day of the week did the client apply for the loan?"
1 reply | 1 retweet | 7 likes

Bogdan Kulynych @hiddenmarkov · 19 h
"Approximately at what hour did the client apply for the loan?"
1 reply | 1 retweet | 6 likes

Bogdan Kulynych @hiddenmarkov · 19 h
"Number of elevators in the building where the client *currently lives*" ...
1 reply | 1 retweet | 8 likes

Bogdan Kulynych @hiddenmarkov · 19 h
"Number of enquiries to Credit Bureau about the client one hour/day/month before application"
2 replies | 1 retweet | 5 likes

Bogdan Kulynych @hiddenmarkov · 19 h
... I don't doubt these might be "correlated" with defaulting on loans, but someone at these agencies must realize that using these features for individual-level decisions will result in absurd outcomes? ...

AI sucks...

Image classification



(A) **Cow: 0.99**, Pasture: 0.99, Grass: 0.99, No Person: 0.98, Mammal: 0.98



(B) No Person: 0.99, Water: 0.98, Beach: 0.97, Outdoors: 0.97, Seashore: 0.97



(C) No Person: 0.97, **Mammal: 0.96**, Water: 0.94, Beach: 0.94, Two: 0.94

Use of spurious correlations.

AI sucks...

Spoiler:

A **spurious correlation** is a correlation that **results** from a **non-causal path**.

$$P(Y|X) - P(Y|do(X))$$

AI sucks...

- We want to minimize the **Empirical Risk**.
- We want to maximize **robustness** against **changes** in data distribution.
- We want to maximize **robustness** against **adversarial attacks**.
- We want to be able of **explaining** my predictions to different **stakeholders**.
- We want to measure and mitigate **harmful biases** (**discrimination**).
- We want to use predictions to support a **decision** that may influence the outcome they aim to predict (**performative predictions**).
- Etc.

AI sucks...

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All these considerations involve causal thinking.

Causal Data Science

Causal Data Science

OBSERVATIONAL DATASET (passive observation of the world)

	Sex	Race	Height	Income	Marital Status	Years of Educ.	Liberalness
R1001	M	1	70	50	1	12	1.73
R1002	M	2	72	100	2	20	4.53
R1003	F	1	55	250	1	16	2.99
R1004	M	2	65	20	2	16	1.13
R1005	F	1	60	10	3	12	3.81
R1006	M	1	68	30	1	9	4.76
R1007	F	5	66	25	2	21	2.01
R1008	F	4	61	43	1	18	1.27
R1009	M	1	69	67	1	12	3.25

Let's consider some different features in this dataset, (X, Y, Z) .

Which can of questions can we answer from this dataset?

Causal Data Science

X

Y

Z

	Sex	Race	Height	Income	Marital Status	Years of Educ.	Liberal-ness
R1001	M	1	70	50	1	12	1.73
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Causal Data Science

Q1: Which is the *expected income* Y that would have been observed if an individual had $X = x$ and $Z = z$?

Association (or prediction) is using data to map some features of the world (the inputs) to other features of the world (the outputs) based on the observed $p(X, Y, Z)$. For example, $\mathbb{E}(Y | X, Z)$.

All we need to do prediction is a dataset sampled from $p(X, Y, Z)$ and some inference tools (statistical inference & machine learning).

Causal Data Science

Q1: Which is the *expected income* Y that would have been observed if an individual had $X = x$ and $Z = z$?

Mapping observed inputs to observed outputs is a **natural candidate for automated data analysis** because this task only requires

- 1) a large **dataset** with inputs and outputs, 2) an **algorithm** that establishes a mapping between inputs and outputs, and 3) a metric to assess the performance of the mapping, often based on a gold standard.

Causal Data Science

Causal effect of Race on Income

Q2: Estimate the **mean income** \bar{Y} that would have been observed if all individuals had ($X = 1$) vs. if they had ($X \neq 1$).

Causal Inference is using data to **predict certain features of the world if the world had been different is some aspect**. We cannot get these data by passive observation of the world! The world was real only in a way!

Causal Data Science

Causal effect of Race on Income

Q2: Estimate the **mean income** \bar{Y} that would have been observed if all individuals had $(X = 1)$ vs. if they had $(X \neq 1)$.

Answers to causal questions cannot be derived exclusively from $p(X, Y, Z)$. Answering a causal question (yes, sometimes is possible!) typically requires a combination of data, analytics, and **expert causal knowledge**.

Causal Data Science

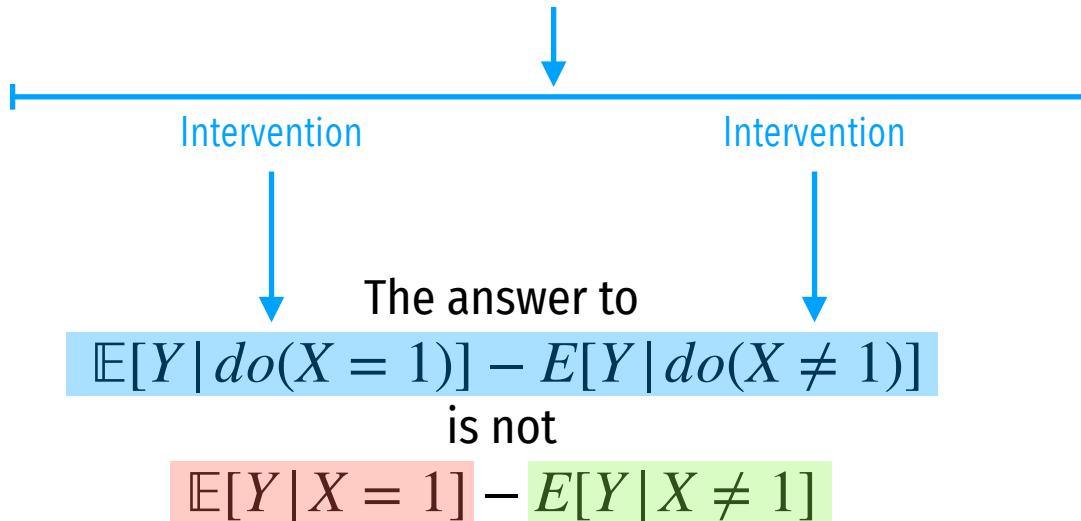
	Sex	Race	Height	Income	Marital Status	Years of Educ.	Liberalness
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$$\mathbb{E}[Y | do(X = 1)] - E[Y | do(X \neq 1)] ?$$

Causal effect of Race on Income

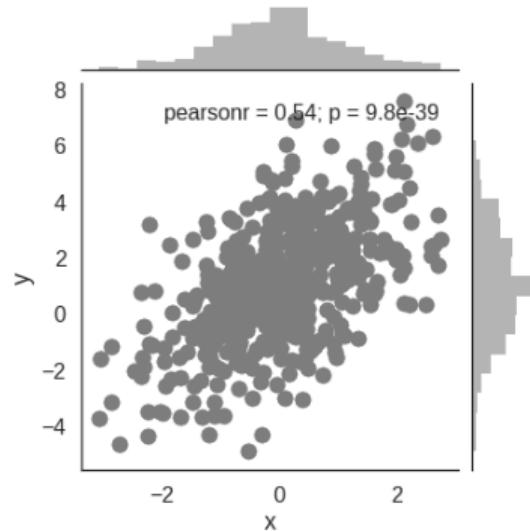
Causal Data Science

Causal effect of Race on Income



Causal Data Science

In order to understand what is $p(Y | do(X = x))$, let's suppose I have observed $p(X, Y)$.



This is all we need to compute $p(Y | X)$. We can give an answer to any associational question.

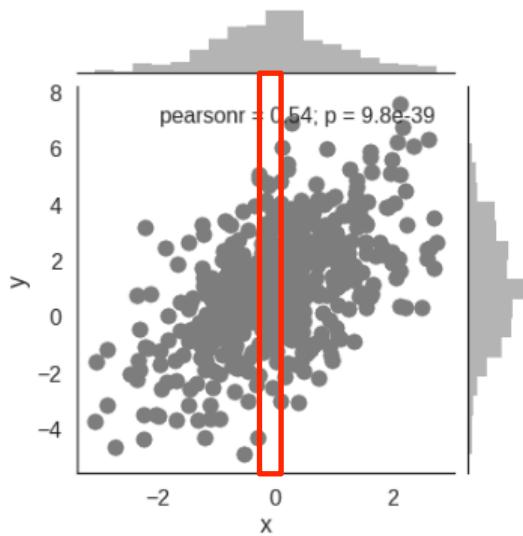
For example:

- What is the expected value of Y if we observe $X = 0$, $\mathbb{E}(Y | X = 0)$? (**Regression**)
- What is the expected MAX/MIN/MEDIAN value of Y if we observe $X = 0$? (**Quantile regression**)
- Etc.

Causal Data Science

- What is the expected value of Y if we observe $X = 0$, $\mathbb{E}(Y | X = 0)$? (**Regression**)

$$p(Y | X = 0)$$



<https://www.inference.vc/causal-inference-2-illustrating-interventions-in-a-toy-example/>

Causal Data Science

OBS

$p(Y | X)$

INT

$p(Y | do(X = x))$

OBS and INT are not generally the same!

**Let's consider three generative models
corresponding to the same $p(X, Y)$**

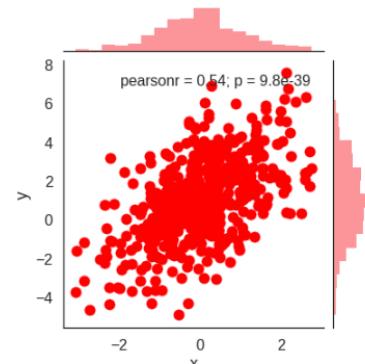
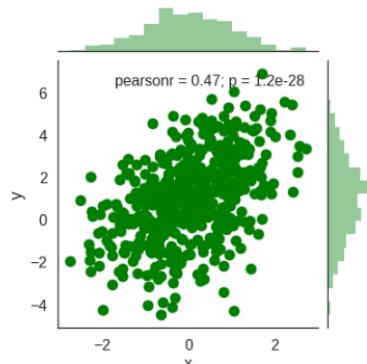
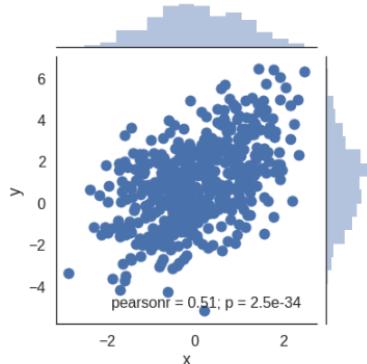
Causal Data Science

Generative Models

```
x = randn()  
y = x + 1 + sqrt(3)*randn()
```

```
y = 1 + 2*randn()  
x = (y-1)/4 + sqrt(3)*randn()/2
```

```
z = randn()  
y = z + 1 + sqrt(3)*randn()  
x = z
```



Based on the joint distribution the three scripts are indistinguishable.

<https://www.inference.vc/causal-inference-2-illustrating-interventions-in-a-toy-example/>

Causal Data Science

Intervention $p(Y | do(X = 3))$

```
x = randn()
```

```
x = 3
```

```
y = x + 1 + sqrt(3)*randn()
```

```
x = 3
```

```
y = 1 + 2*randn()
```

```
x = 3
```

```
x = (y-1)/4 + sqrt(3)*randn()/2
```

```
x = 3
```

```
z = randn()
```

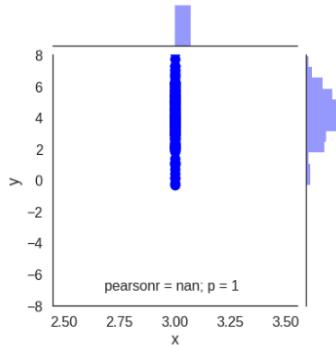
```
x = 3
```

```
x = z
```

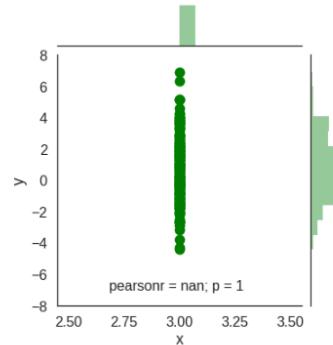
```
x = 3
```

```
y = z + 1 + sqrt(3)*randn()
```

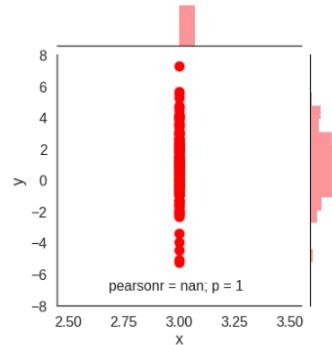
```
x = 3
```



$p(Y | do(X = 3))$



$p(Y | do(X = 3))$



$p(Y | do(X = 3))$

The joint distribution of data $p(X, Y, Z)$ alone is insufficient to predict behavior under interventions.

<https://www.inference.vc/causal-inference-2-illustrating-interventions-in-a-toy-example/>

Causal Data Science

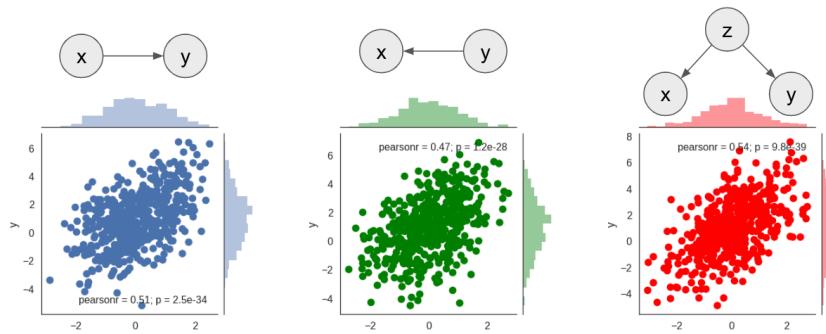
An intervention can be understood as a **modification of the generative model of the data, producing a different probability distribution:**
 $p(\text{do}(X = 3), Y, Z)$

Generative Models

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x = randn()  
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y = 1 + 2*randn()  
x = (y-1)/4 + sqrt(3)*randn()/2
```

```
z = randn()  
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x = z
```



Directed Acyclic Graphs (DAG).

No assumptions about the exact form of the functional relationships are needed. The only requirement is that causal relationships are **acyclic**.

Causal Data Science

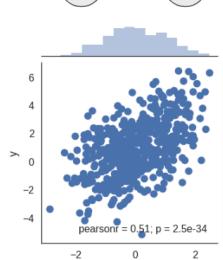
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 $p(\text{do}(X = 3), Y, Z)$

Generative Models

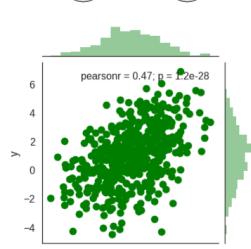
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```

```
y = 1 + 2*randn()  
x = (y-1)/4 + sqrt(3)*randn()/2
```

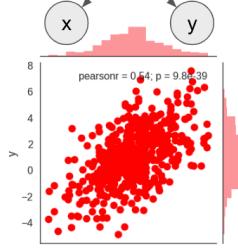
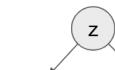
```
z = randn()  
y = z + 1 + sqrt(3)*randn()  
x = z
```



X is the cause of Y



Y is the cause of X



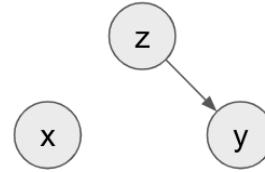
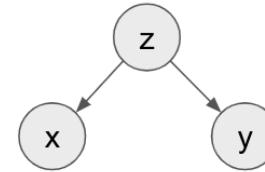
X and Y are not causally related (but they are associated!)

<https://www.inference.vc/causal-inference-2-illustrating-interventions-in-a-toy-example/>

Causal Data Science

What is an intervention?

Graphically, to **simulate the effect of an intervention**, you **mutilate** the graph by removing all edges that point into the variable on which the intervention is applied, in this case x .



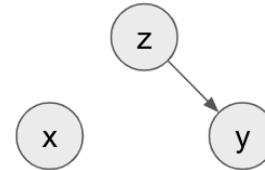
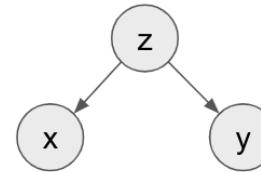
$$P(Y | do(X = x)) = P(Y | X = x)$$

$$P(Y | do(X = x)) = P(Y)$$

$$P(Y | do(X = x)) = P(Y)$$

Causal Data Science

What is an intervention?



$$P(Y | do(X = x)) = P(Y | X = x)$$

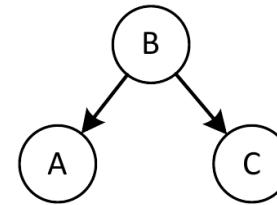
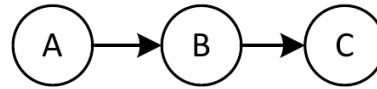
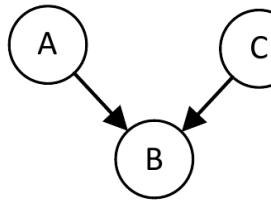
$$P(Y | do(X = x)) = P(Y)$$

$$P(Y | do(X = x)) = P(Y)$$

Just by looking at the causal diagram, we are now **able to predict** how the scripts are going to behave under the intervention $X = 3$.

Causal Data Science

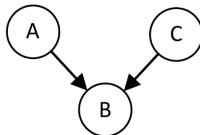
- The primary language for modeling causal mechanisms and expressing our assumptions is the **language of causal graphs**.



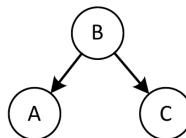
- Causal graphs encode our domain knowledge about the causal mechanisms underlying a system or phenomenon under study.
- Causal graphs are assumed to be **acyclic**. This is why they are called **DAGs (Directed Acyclic Graphs)**.

Causal Data Science

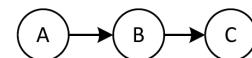
- Fundamentally, a causal graph describes a **non-parametric data-generating process** over its nodes.
- By specifying independence and dependence between the nodes, the graph constrains relationship between generated variables corresponding to those nodes.



B is a **collider** for A and C
A and B create an **inverted fork** to B
A and C are independent



B is a **confounder**
B creates a **fork** to A and C
A and C are not independent.
A and C are independent conditional on B



B forms a **chain** from A to C
A and C are conditionally independent given B

Causality Theory

A DAG provides enough extra-data information
(in terms of conditional independences)

**to answer many causal queries,
even with the data generating process hidden.**

Causal Thinking

Basic Concepts: Causal Effect

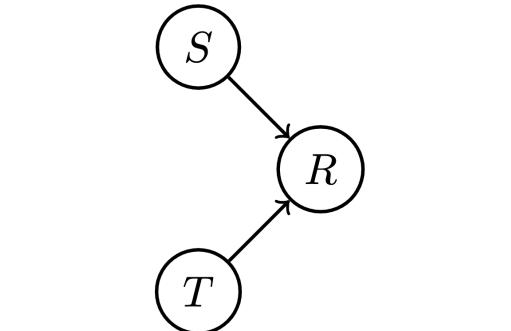
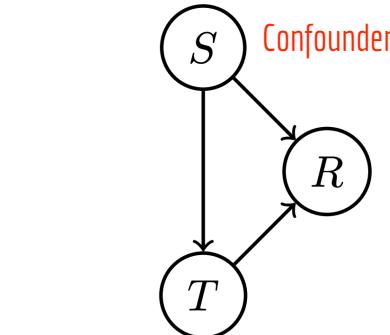
Symptoms, Treatment, Recovery

- The **average treatment/causal effect** (ATE) of T on R :

$$\mathbb{E}[R \mid do(T = 1)] - E[R \mid do(T = 0)]$$

- The **conditional average treatment/causal effect** (CATE):

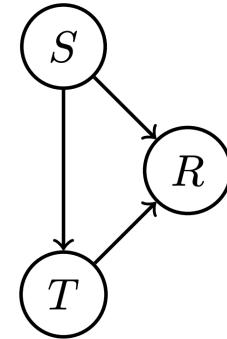
$$\mathbb{E}[R \mid do(T = 1), S] - E[R \mid do(T = 0), S]$$



Intervened graph
 $do(T = t)$

Basic Concepts: Counterfactual

- **Counterfactuals:** hypothetical result that an intervention may have on an individual for whom we have already observed a different *factual* outcome.
 - Counterfactuals allow us to mix factual information with alternative scenarios.
 - Explainability and Fairness applications.
- Given a certain patient with symptoms s , who was not given a treatment and didn't recover, **would they have recovered had we given them the treatment?**
- The **individual treatment/causal effect** (ITE):



$$\mathbb{E}[R_i | do(T_i = 1)] - E[R_i | do(T_i = 0)]$$

Causal Thinking Process

1. Asking a causal/counterfactual query (ATE, CATE, ITE,...)
2. Gathering knowledge from experts
3. Building a DAG
4. **Identifying** the causal query
5. Gathering data.
6. Computing and estimand/building a SCM
7. Answering the causal/counterfactual query

Asking a causal query

Salary Dataset

→ Variables:

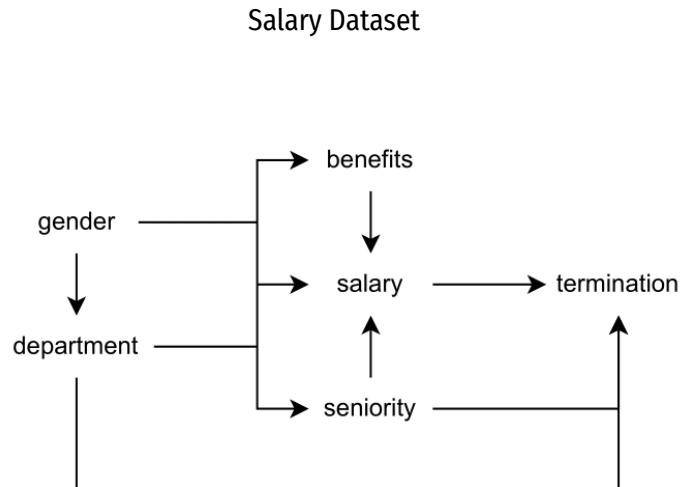
- Gender.
- Department.
- Benefits.
- Seniority.
- Salary.
- Termination.

→ Possible interesting queries:

- $\mathbb{E}[S \mid do(G = male)] - \mathbb{E}[S \mid do(G = female)]$:
ATE of gender (binary) on salary.
- $\mathbb{E}[S_i^* \mid do(G_i^* = male), G_i = female, S_i = s]$:
given a particular woman i with salary s , **counterfactual** salary when male.

Gathering knowledge and data

- We need to find the corresponding causal graph.
 - Causal Discovery algorithms.
 - Domain Experts.
 - Experiments.



Identifiying a causal query

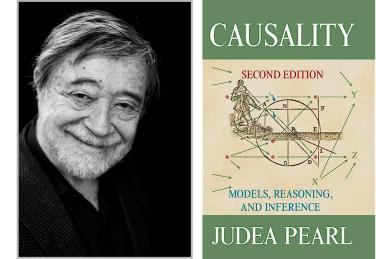
There are two ways to measure the **causal relationship** between two variables, S and G :

1. The easiest way is an **intervention** in the real world: You **randomly** force G to have different values and you measure S .

This is what we do in Randomized Clinical Trial (RCT) or in an A/B Test.

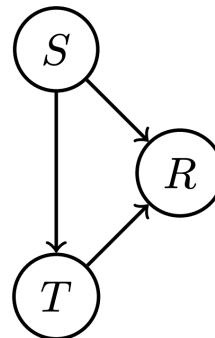
This is not always feasible (because of **practical, ethical or economical** reasons)

Identifying a causal query



2. If the query is **identifiable** we can compute an estimand.

For example, in this case, **do-calculus** allows us to massage $p(S, R, T)$ until we can express $p(R | do(T))$ in terms of various marginals, conditionals and expectations under $p(S, R, T)$.

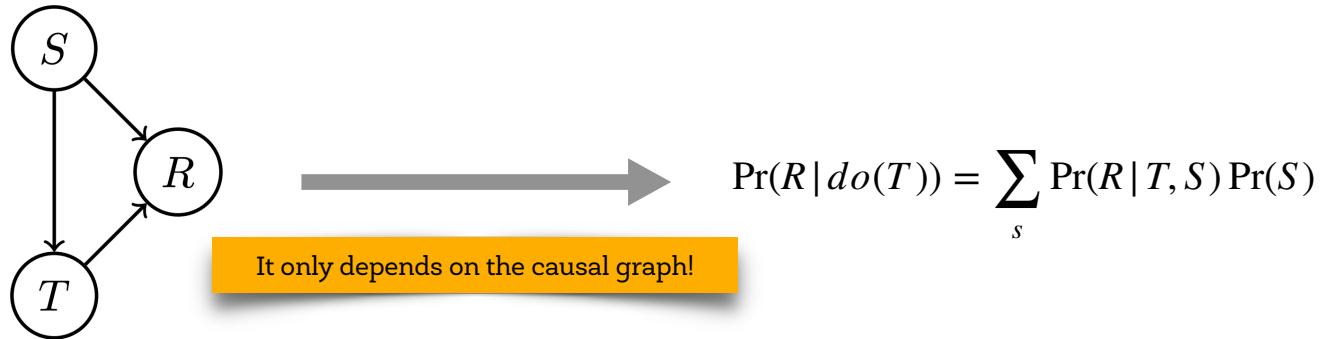


$$\Pr(R | do(T)) = \sum_s \Pr(R | T, s) \Pr(s)$$

Identifying a causal query

2. If the query is **identifiable** we can compute an estimand.

For example, in this case, **do-calculus** allows us to massage $p(S, R, T)$ until we can express $p(R | do(T))$ in terms of various marginals, conditionals and expectations under $p(S, R, T)$.



Identifying the causal query

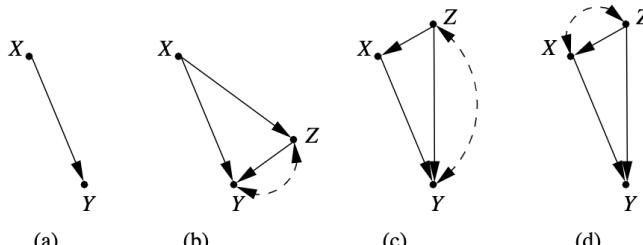
- Causal query \mathcal{Q} , e.g., $\mathcal{Q} := \mathbb{E}[S \mid do(G = male)] - \mathbb{E}[S \mid do(G = female)]$.
 - It contains interventional terms, so we can't use the dataset directly.
 - **Identification:** transform every interventional term into an expression using only observational terms ⇒ **estimand**.
 - There are **automated algorithms** that do this work for us.

Identifying the causal query

Salary Dataset

Given a causal query for a certain DAG, we say it is **identifiable** if we can derive an statistical estimand (**only using observational terms**) for this query using the rules of **do-calculus**.

The **do-calculus** is an axiomatic system for replacing probability formulas containing the **do** operator with ordinary conditional probabilities. It consists of three axiom schemas that provide **graphical criteria** for when certain substitutions may be made.



Causal graphs where $P(y|do(x))$ is identifiable

Dashed lines correspond to **unobserved confounders**, associations produced by unobserved variables.

Source: Complete Identification Methods for Causal Inference, PhD Thesis, University of California. I.Spitser

Identifying the causal query

The screenshot shows a GitHub repository page for the user 'pedemonte96' named 'causaleffect'. The repository is public and has 3 issues, 2 pull requests, 19 commits, 2 branches, and 2 tags. The repository was created by 'pedemonte96' on 12 Jul 2020. The commits listed include creating CONTRIBUTING.md, updating issue templates, improving documentation, adding examples, updating README, and removing dependencies. The repository uses Python and follows the MIT License. It has two releases: v0.0.2 (Latest) and + 1 release. There are no packages published.

pedemonte96 / causaleffect Public

Code Issues 3 Pull requests Actions Projects Wiki Security Insights

main 2 branches 2 tags Go to file Add file Code

pedemonte96 Create CONTRIBUTING.md 320d16f on 12 Jul 19 commits

.github/ISSUE_TEMPLATE Update issue templates 3 months ago

causaleffect improved verbose d-separation 4 months ago

documentation improved documentation 4 months ago

examples fixed example and added documentation 4 months ago

images updated readme 4 months ago

tests add id tests 3 months ago

.gitignore causal effect added 4 months ago

CODE_OF_CONDUCT.md Create CODE_OF_CONDUCT.md 3 months ago

CONTRIBUTING.md Create CONTRIBUTING.md 3 months ago

LICENSE Create LICENSE 3 months ago

README.md removed pycairo dependency 4 months ago

pyproject.toml build done 4 months ago

requirements.txt removed pycairo dependency 4 months ago

setup.py Update setup.py 3 months ago

About

Python package to compute conditional and non-conditional causal effects.

Readme MIT License

Releases 2

v0.0.2 (Latest) on 19 Jun

+ 1 release

Packages

No packages published Publish your first package

Languages

Python 100.0%

Identifying the causal query

```
import causaleffect  
  
G = causaleffect.createGraph(['X<->Y', 'Z->Y', 'X->Z', 'W->X', 'W->Z'])  
causaleffect.plotGraph(G)
```

```
P = causaleffect.ID({'Y'}, {'X'}, G)  
P.printLatex()
```

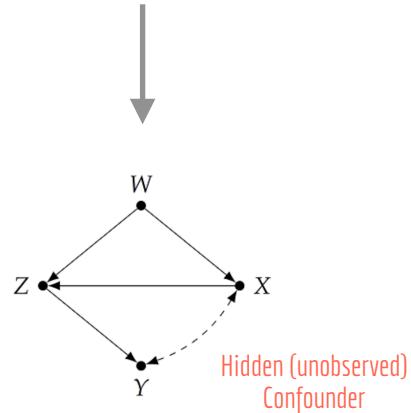
The code above computes the causal effect, and returns a string encoding the distribution in LaTeX notation:

```
'\sum_{w,z} P(w)P(z|w,x)\left(\sum_x P(x|w)P(y|x,w,z)\right)'
```

This string, in LaTeX, is

$$\sum_{w,z} P(w)P(z|w,x) \left(\sum_x P(x|w)P(y|x,w,z) \right)$$

$$p(X, W, Z, Y)$$



Building a causal model

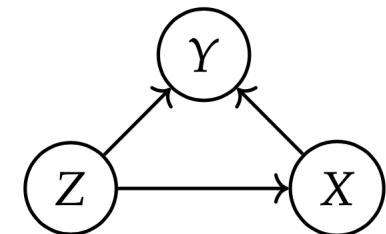
→ Once we have an estimand, we need to build **models** to use it for our estimation.

$$\rightarrow \mathcal{Q} := \mathbb{E}[Y \mid do(X = x)] = \mathbb{E}_Z[\mathbb{E}_{Y|x,Z}[Y]].$$

→ We need to model the $f(x, Z) := \mathbb{E}_{Y|x,Z}[Y]$ term.

→ If Y is binary, with a ML classifier.

→ If Y is continuous, with a ML regressor.



Answering the query

→ Now that we have our ML model, we can follow the **estimand** formula:

$$\rightarrow Q := \mathbb{E}[Y \mid do(X = x)] = \mathbb{E}_Z[\mathbb{E}_{Y|x,Z}[Y]].$$

→ The \mathbb{E}_Z expectation can be estimated by averaging dataset samples:

$$Q = \mathbb{E}_Z[\mathbb{E}_{Y|x,Z}[Y]] \approx \frac{1}{n} \sum_{i=1..N} f(x, z_i).$$

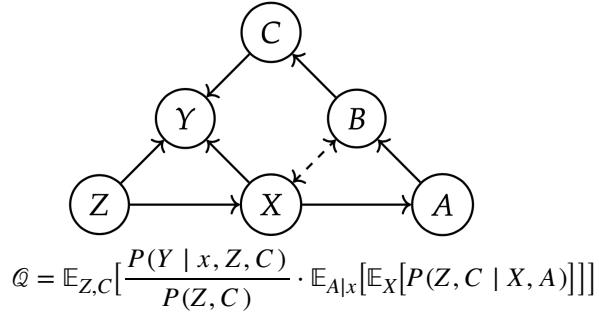
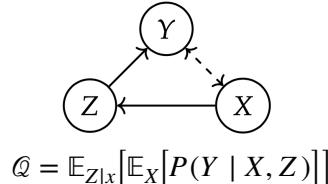
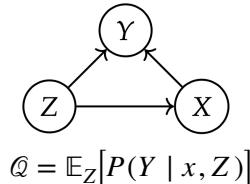
Answering the query

→ The **estimand-based** approach:

1. Derive an **estimand** for our graph & query.
2. Train ML **models** for the terms we need to compute.
3. Follow the estimand formula to obtain an **estimation**.

Answering the query

- However, depending on the graph, even the same query results in different estimands.
- $P(Y \mid do(X = x))$:



Example

From “Causal Inference in AI Education: A Primer”

Example 3.1. AdBot Consider an online advertising agent attempting to maximizing clickthroughs, with $X \in \{0, 1\}$ representing two ads, $Y \in \{0, 1\}$ whether or not it was clicked upon, and $Z \in \{0, 1\}$ the sex of the viewer. A marketing team collects the following data on purchases following ads shown to focus groups to be used by AdBot:

	Ad 0	Ad 1
Male	108/120 (90%)	340/400 (85%)
Female	266/380 (70%)	65/100 (65%)
Total	374/500 (75%)	405/500 (81%)

Table 1. Clickthroughs in the AdBot setting striated by the ad shown to participants in a focus group, and the sex of the viewer.

If the sex of a viewer is not know, which ad is the best choice?

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Simpson's paradox

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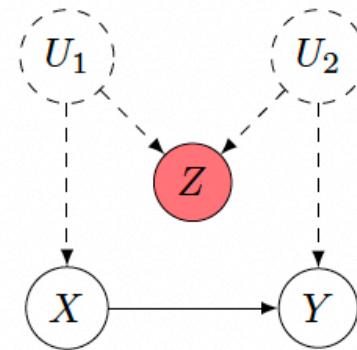
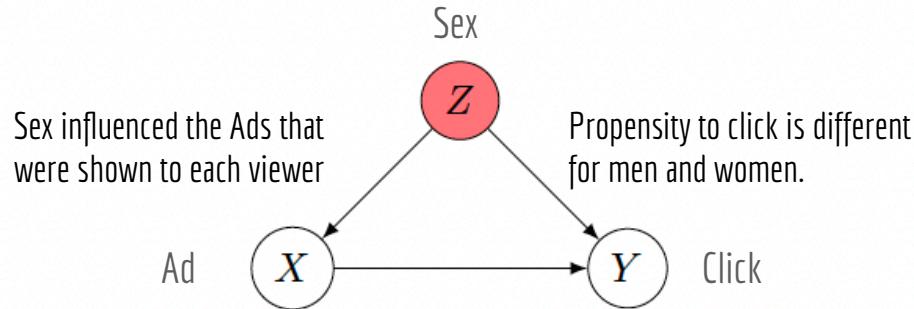
If the sex of a viewer is not know, which ad is the best choice?

Example

From “Causal Inference in AI Education: A Primer”

If the sex of a viewer is not known, which ad is the best choice?

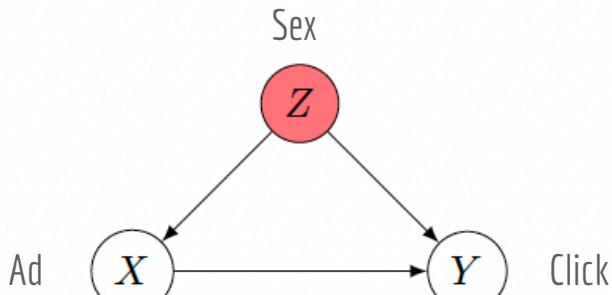
These are two different causal stories:



Relevant question: $p(Y | \text{do}(X_0)) > p(Y | \text{do}(X_1))$?

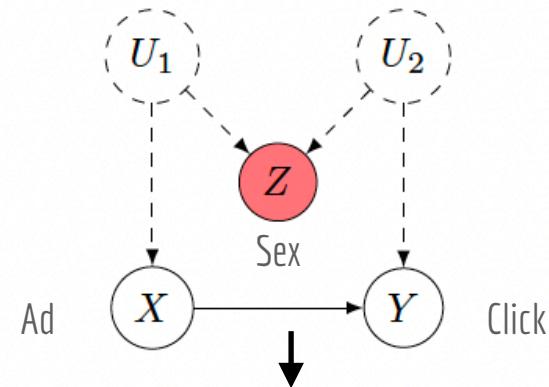
Example

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```
1 G = causaleffect.createGraph(['X->Y', 'Z->Y', 'Z->X'])
2 P = causaleffect.ID({'Y'}, {'X'}, G)
```

$$p(Y | \text{do}(X)) = \sum_z P(Y | X, Z)P(Z)$$



```
1 G = causaleffect.createGraph(['U1<->X', 'U1<->Z', 'U2<->Z', 'U2<->Y', 'X->Y'])
2 P = causaleffect.ID({'Y'}, {'X'}, G)
3 P.printLatex()
```

$$p(Y | \text{do}(X)) = P(Y | X)$$

Example

From “Causal Inference in AI Education: A Primer”

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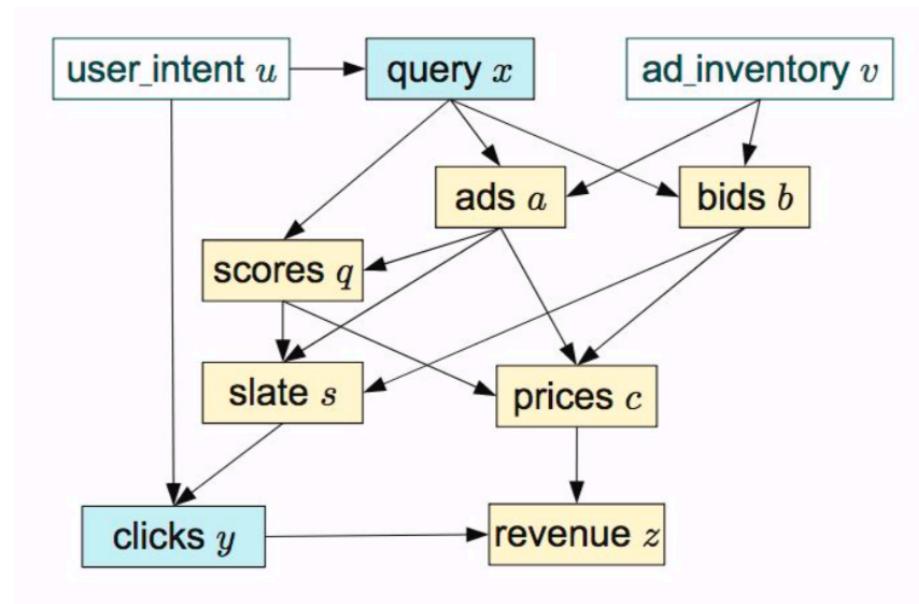
If (a) is our explanation of the data, then AdBot should display Ad0.

If (b) is our explanation of the data, then AdBot should display Ad1.

$$p(Y | \text{do}(X)) = \sum_z P(Y | X, Z)P(Z)$$

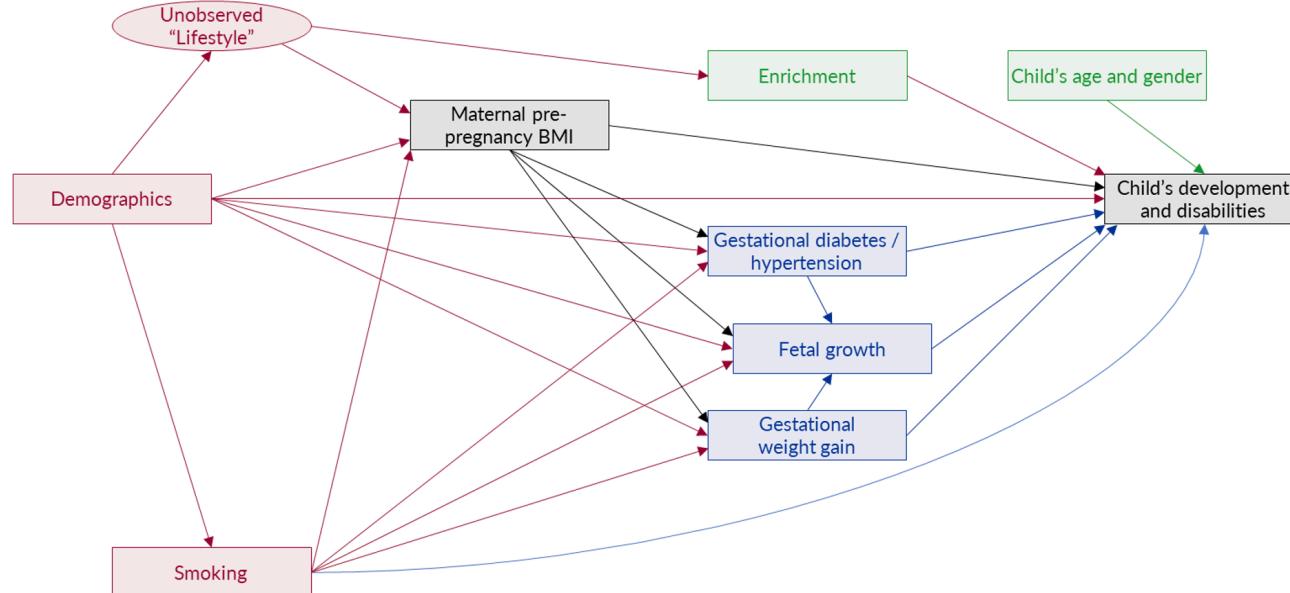
$$\boxed{p(Y | \text{do}(X)) = P(Y | X)}$$

Example



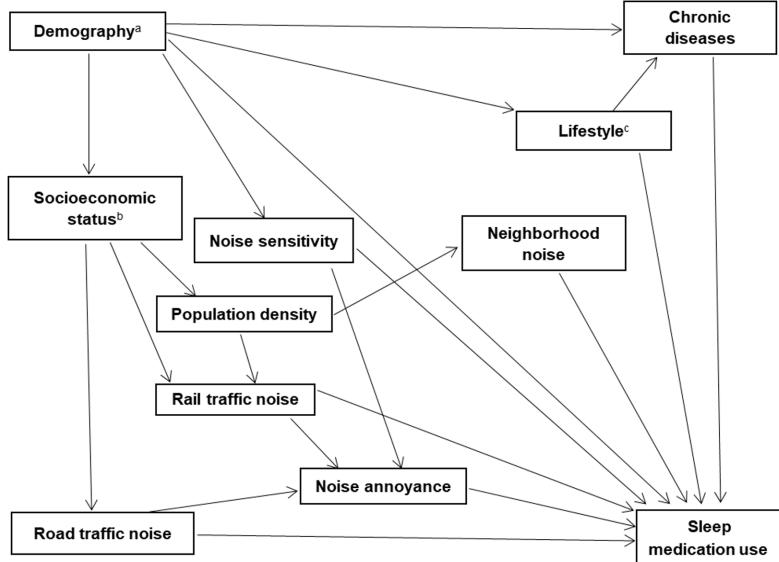
Bottou, Léon, et al. "Counterfactual reasoning and learning systems: the example of computational advertising." *The Journal of Machine Learning Research* 14.1 (2013): 3207-3260.

Example



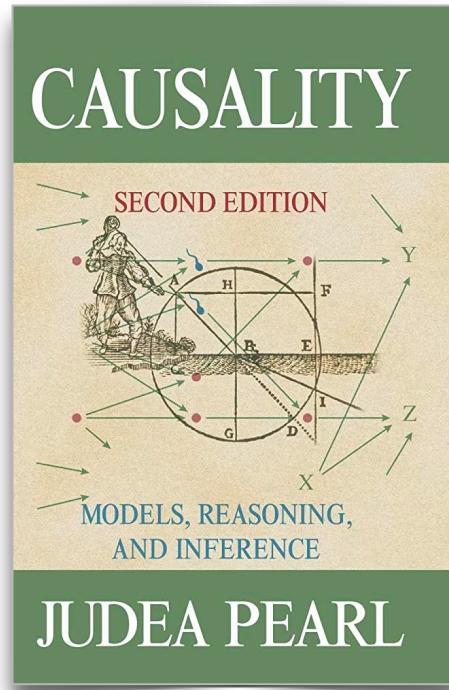
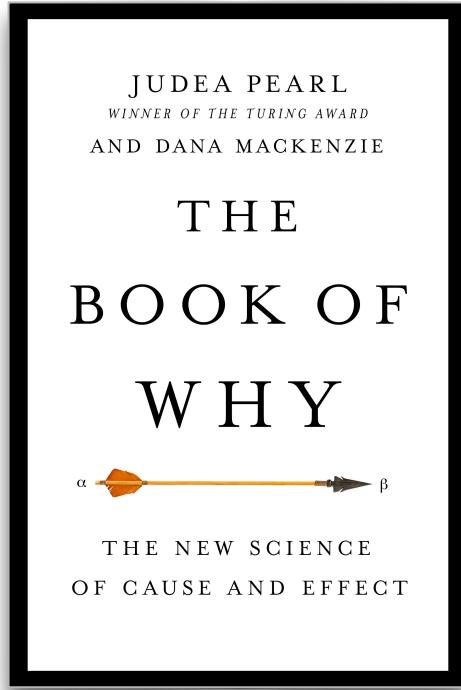
ADAPTED FROM: Hinkle SN, Sharma AJ, Kim SY, Schieve LA. Maternal prepregnancy weight status and associations with children's development and disabilities at kindergarten. *Int J Obes (Lond)*. 2013;37(10):1344-51. DOI: 10.1038/ijo.2013.128 (Figure 1). Freely available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4407562>

Example



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Which causal inference book you should read

Flowchart

<https://www.bradyneal.com/which-causal-inference-book>

