# Learning Bayesian Networks

Discussion on R. Neapolitan’s book, written by D. Gueorguiev

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## Introduction to Bayesian Networks

### Joint Probability Distributions

***Definition 1.1*** Suppose we have sample space containing distinct elements. That is:

.

A function which assigns a real number to each event is called probability function on the set of subsets of if it satisfies the following conditions:

1. for
2. For each event that is not an elementary event,

The pair , will be denoted as ***probability space***.

***Theorem 1.1*** Let , be a probability space. Then

1. .
2. for every .
3. For and such that ,

.

***Definition 1.2*** Let and be events such that . Then the conditional probability of E given F, denoted , is given by:

***Definition 1.3*** Two events are ***independent*** if one of the following hold:

1. and
2. or

***Definition 1.4*** Two events and are ***conditionally independent*** given if and one of the following holds:

1. and

2

1

2

1

1

1

2

2

2

2

1

2

2

Figure: Containing ‘1’ and being a square are not independent, but they are conditionally independent given the object is black and given it is white.

*Example*: Let be the set of all objects on the Figure above. Let us assign a probability of to each object and let **Blue** be the set of all blue objects and **White** be the set of all white objects, Square be the set of all square objects and One be the set of all objects containing ‘1’. Then we have:

,

,

,

***Definition 1.8*** Let a set of random variables be specified such that each has a countably infinite space. A function, that assigns a real number to every combination of values of the ’s such that the value of is chosen from the space of , is called joint probability distribution of the random variables in if it satisfies the following conditions:

1. For every combination of values of the ’s:

1. We have:

Suppose we have events such that for and

. Such events are called ***mutually exclusive and exhaustive***.

The law of total probability says that for any event we have:

***Theorem 1.2 (Bayes)*** Given two events and such that and we have:

Furthermore, given mutually exclusive and exhaustive events , , , such that for all , we have for :

***Definition 1.5*** Given a probability space , , a ***random variable*** is a function of . The set of values can assume is called ***the space*** of . A random variable is said to be ***discrete*** if its space is finite or countable.

***Theorem 1.3*** Let a set of random variables V be given and let a joint probability distribution of the variables in be specified according to Definition 1.8. Let be the Cartesian product of the sets of all possible values of the random variables. Assign probabilities to elementary events in as follows:

These assignments result in a probability function on according to ***Definition 1.1***. Furthermore, if we let denote a function (random variable in the classical sense) on this sample space which maps each tuple in to the value of in that tuple, then the joint probability distribution of the ’s is the same as the originally specified joint probability distribution.

### 

### Markov Condition

***Definition***: ***ancestral ordering*** is such ordering for which if is descendant of , then is on the right of

***Definition 1.9*** Suppose we have a joint probability distribution of the random variables in some set and a DAG = . We say that satisfies ***the Markov condition*** if for each variable conditionally independent of the set of all of its non-descendants given the set of all its parents. If we denote the sets of parents and non-descendants of by and , respectively, then

When satisfies *the Markov condition*, we say and satisfy Markov condition with each other.

If is a root, then its parent set is empty. So, in this case it means that the Markov condition means is independent of - . But implies . We have . So, we can rewrite the Markov condition as:

*Example*: Let be the set of objects on the Figure below and let assign a probability of to each object. Let the random variables V, S and C are defined as:

|  |  |  |
| --- | --- | --- |
| Variable | Value | Outcomes mapped to this Value |
|  |  | *All objects containing ‘1’* |
|  |  | *All objects containing ‘2’* |
|  |  | *All square objects* |
|  |  | *All round objects* |
|  |  | *All black objects* |
|  |  | *All white objects* |

2

1

2

1

1

1

2

2

2

2

1

2

2

Figure: Containing ‘1’ and being a square are not independent, but they are conditionally independent given the object is black and given it is white.

We have shown earlier that . Therefore, satisfies the Markov condition if is the DAG (a), (b), or (c) in the Figure below. However, does not satisfy the Markov condition if is the DAG in Fig. (d) because does not hold.

Figure: The probability distribution in the Example above satisfies the Markov condition only for the DAGs in (a), (b), and (c).

*Example*: Consider the DAG on the Figure below. If satisfied the Markov condition for some probability distribution , we would have the following conditional independencies:

|  |  |  |
| --- | --- | --- |
| Node | PA | Conditional Independency |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

Recall that the number of terms in a joint probability distribution is exponential in terms of the number of variables. So, in the case of a large instance, we could not fully describe the joint distribution by determining each of the values directly. We will show that if satisfies the Markov condition, then equals the product of its conditional probability distributions of all nodes given the values of their parents in whenever these conditional distributions exist. For the joint probability distribution P of the variables in the DAG on the Figure below for all values of , , , , and we would have

whenever the conditional probabilities on the right exist. Notice that if one of them does not exist for some combination of the values of the variables, then or or which implies for that combination of values. So the Equality above must hold for all nonzero values of the joint probability distribution plus some zero values.

Figure: a DAG illustrating the Markov condition

***Theorem 1.4*** If satisfies *the Markov condition*, then is equal to the product of its conditional distributions of all nodes given values of their parents, whenever these conditional distributions exist.

*Proof*: We prove the case where is discrete. Order the nodes in their ancestral ordering. Let , , …, be the resultant ordering. For a given set of values , , …, let be the subset of these values containing the values of ’s parents. We need to show that whenever for ,

We show this using induction on the variables of the network. Assume for some combination of values of the for

*Induction base* :

Since is empty .

*Induction hypothesis* :

Suppose for this combination of values of the that:

*Induction Step*: Prove assuming that the hypothesis for is true

(1.7)

There are two cases:

*Case 1*: for this combination of values:

(1.8)

Clearly (1.8) implies

Furthermore, due to (1.8) and the induction hypothesis, there is some , where such that . So (1.7) holds.

*Case 2*: For this combination of values:

In this case

The first equality is due to the rule for conditional probability, the second is due to the Markov condition and the third one is due to the induction hypothesis.

***Theorem 1.5*** Let a DAG be given in which each node is a random variable and let a discrete conditional probability distribution given the values of its parents in be specified. Then the product of these conditional distributions yields a joint probability distribution of the variables and satisfies the Markov condition.

*Proof*: Order the nodes according to the ancestral ordering. Let , , , be the resultant ordering. Next define:

where is the set of parents of in and is the specified conditional probability distribution. First, we show that this does indeed yield joint probability distribution. Clearly, for all values of the variables. Therefore, to show that we have joint distribution Definition 1.8 and Theorem 1.3 imply that we only need to show that the sum of , as the variables are ranging through their all possible values, equal to 1. To that end:

.

To be done: *show that the specified conditional distributions are the conditional distributions which they notationally represent in the joint distribution*

Finally, we show the Markov condition is satisfied. To do this, we need to show for that whenever if and then , where is the set of non-descendants of in . Since , we only need to show that . First, for a given , order the nodes so that all and only descendants of precede in the ordering. Note that this ordering depends on whereas the ordering in the first part of the proof does not. Clearly then:

Let

= {, ,, }

In what follows means the sum as the variables in go over all of their possible values. Furthermore, notation such as means the variable has a particular value; notation such as means all variables in the set have particular values; and notation such as means some variables in the set may not have particular values. We have that:

In the second to last step, the sums are each equal to one for the following reason. Each is a sum of a product of conditional probability distributions specified for a DAG. In the case of the numerator, that DAG is the subdigraph of our original digraph , consisting of the variables in , and in the case of the denominator, it is the subdigraph consisting of the variables in . Therefore, the fact that each of those sums equals 1 follows from the first part of the proof. Notice that the theorem requires that the specified conditional distributions be discrete. Often in the case of continuous distributions it still holds. For example, it holds for Gaussian distributions. However, it does not hold for all continuous conditional distributions. See [[Dawid and Studeny, 1999]](https://github.com/dimitarpg13/learning_bayesian_networks/blob/main/articles/ConditionalProductsAnAlternativeApproachtoConditionalIndependenceDawid1999.pdf) for example in which no joint distribution having the specialized distributions as conditionals even exist.

## Bayesian Networks

***Definition*** (*Bayesian Network*)

Let be the joint probability distribution of the random variables in some set , and be a DAG. We call a Bayesian network if satisfies the Markov condition. Owning to *Theorem 1.4*, is the product of its conditional distributions in and this is the way is always represented in a Bayesian network. Furthermore, owing to *Theorem 1.5*, if we specify a DAG and any discrete conditional distributions (and many continuous ones), we obtain a Bayesian network. This is the way Bayesian networks are constructed in practice.

### Creating Bayesian Network using Causal Edges

***Definition*** (*causal DAG*) Given a set of random variables , if for every , in we draw an edge from to if and only if is a direct cause of relative to , we call the resulting DAG a ***causal DAG***.

#### Ascertaining Causal Influences Using Manipulation

Some of what follows is based on a similar discussion to [[Cooper, 1999]](https://github.com/dimitarpg13/learning_bayesian_networks/blob/main/articles/OverviewoftheRepresentationandDIscoveryofCausalRelationshipsUsingBayesianNetworksCooper1999.pdf).

***Definition*** (*Operational method for identifying causal relationships*)

If the action of making some variable take some value sometimes changes the value taken by variable , then we assume is responsible for sometimes changing ’s value, and we conclude is a **cause** of . More formally, we say we **manipulate** when we force to take some value and we say causes if there is some manipulation of which leads to a change in the probability distribution of .

We assume that if manipulating leads to a change of the probability distribution of , then obtaining a value by any means also leads to a change of the probability distribution of . So, we assume that causes and their effects are statistically correlated. Note that in general variables can be statistically correlated without one being the cause of the other. A manipulation consists of a randomized controlled experiment (**RCE**) using some specific population of entities in some specific context. The causal relationship discovered is then relative to this population and this context.

Let us discuss how manipulation proceeds. We first identify the population of entities we wish to consider. Our random variables are features of these entities. Next, we ascertain the causal relationship we wish to investigate. Suppose we are trying to determine if variable is the cause of variable . For every entity selected, we manipulate the value of so that each of its possible values is given to the same number of entities (if is continuous, we choose the values of according to uniform distribution). After the value of is set for a given entity we measure the value of for that entity. The more the resultant data shows a dependency between and the more the data supports that casually influences . The manipulation of can be represented by a variable that is external to the system being studied. There is one value of for each value of , the probabilities of all values of are the same, and when equals , equals . That is, the relationship between and is deterministic. The data supports that causally influences to the extent the data indicates for . Manipulation is actually a special kind of causal relationship that we assume exists primordially and is within our control so that we can define and control other causal relationships.

***Example*** (*Possible causal relationships*)

Let and be random variables. The actual values of and are unimportant to the current discussion. We could use either continuous or discrete values. If caused then, indeed, they would be statistically correlated but this would be the case if caused , or if they had some hidden common cause . If we represent causal influence by a directed edge, we have the following 5 possibilities:

1. (b) (c) (d) (e) (f)

-----> <----- ------ > \_\_ ---x---

^ | | | | |

|\_\_\_\_\_\_| v v -----> <------

1. Shows the conjecture that causes
2. Shows the conjecture that causes

When we do not have domain knowledge (a) and (b) seem equally reasonable.

1. shows causal loop or feedback.
2. and have some hidden common cause which accounts for their statistical correlation.
3. we are observing a population in which all individuals have some (possibly hidden) effect of both and . We say a node is **instantiated** when we know its value for the entity currently being modeled. So, we are saying Y is instantiated to the same value for all entities in the population we are observing. This is depicted here by putting the node in **~~bold strikethrough~~**. Ordinarily, an instantiation of a common effect causes a dependency between its causes because each cause explains away the occurrence of the effect, thereby making the other cause less likely. This psychological phenomenon is called **discounting**. So, if this were the case discounting would explain the correlation between and . This type of dependency is called **selection bias**.
4. and are not related causally at all. The most notable example is when our entities are points in time and our random variables are values of properties at these different points in time. Such random variables are often correlated without having an apparent causal connection.

It may not be obvious why two variables with common cause would be correlated. Consider the present example. Suppose that is a common cause of and and neither nor caused the other. Suppose is a common cause of and and neither nor caused the other. Then and are correlated because causes , and are correlated because causes , which implies that and are correlated transitively through . Here is a more detailed explanation: for this example, suppose is a value of that has causal influence on taking value and on taking value . Then if had value , each of its causes would become more probable because one of them should be responsible. So . Now since the probability of has gone up, the probability of would also go up because h1 causes g1. Therefore, , which means and are correlated.

***Example*** (The company ’s *manipulation study*)

\_\_\_\_\_\_\_\_\_\_

| |

M ----- > | F ------- > G |

|\_\_\_\_\_\_\_\_\_\_|

Since cannot conclude that causes which is remediation of the disease from their mere correlation alone they did a test manipulation to test this conjecture. The study was done on men in a particular age group which exhibited the symptom of the disease which is supposed to cure. of the men were given and were given placebo. Let us define the variables for the study including the manipulation variable.

Variable Value When The Variable Takes This Value

subject takes given quantity of the substance

subject takes given quantity of placebo

subject no longer experiences symptoms of

subject still experiences symptoms of

subject is chosen to take given quantity of the substance

subject is chosen to take given quantity of placebo

The figure above shows the conjecture that causes and the **RCE** used to test this conjecture. The gray line around the system being modeled indicates that the manipulation comes from outside the system. The edges in that graph represent causal influences. The **RCE** supports the conjecture that causes to the extent that the data supports . Specifically, it was found that and .

***Example*** (*Causal Mediaries*)

---- > ---- >

– causal mediary

Let us suppose that there is an agent accounted by another random variable such that and are in causal relationship. Let us suppose that had enough information to conclude that and are in causal relationship as well. These two causal relationships are depicted on the Graph above.

Could have assumed that had a causal effect on through and thus avoiding to do the manipulation **RCE**? The answer is No. It is possible that certain minimal level of the agent is necessary to trigger the disease , more than that minimal level of has no further effect on and the substance is not capable of lowering the level of beyond that minimal level. That is, it may be that has causal effect on and has causal effect on and yet has no causal effect on .

***Definition*** (*faithfulness condition*) If we identify that causes and causes , and and are probabilistically independent we say that the probability distribution of the variables is not **faithful** to the DAG representing their causal relationships. In general, we say satisfies the **faithfulness condition** if satisfies Markov condition and the only conditional independencies are entailed by the Markov condition. So, if and are independent, the probability distribution does not entail the faithfulness condition in the DAG of the figure above because this independence is not entailed by the Markov condition.

Notice that the variable was not in the DAG on the figure above and if probability distribution did satisfy the faithfulness condition there would have been an edge from F directly to G instead of taking the directed path through A. It seems that we can usually conceive of intermediate unidentified variables along each edge. Consider the following example:

***Example*** (*causal mediary*): If is an event of striking a match, and is an event of the match catching on fire, and no other events are considered then is a direct cause of . If, however, we added , the sulfur on the match achieved sufficient heat to combine with oxygen then we could no longer say that directly caused but rather caused and caused . Accordingly, we say that is a **causal mediary** between and if causes and causes .

***Note*** (*observer-dependent variables*): In that intuitive explanation a variable name is used to stand also for the value of the variable. For example, is a variable whose value is on-fire or not-on-fire and is also used to represent that the match is on fire. Clearly, we can add more causal mediaries. For example, we could add the variable D representing whether the match tip is abraded by a rough surface. C, then, would cause D, which in turn would case B, etc. We see that the set of **observable** variables are **observer-dependent**. An individual, given large amount of sensory input, selectively records discernible events and develops cause-effect relationships between them. Therefore, rather than assuming that there is an objective set of causally related variables, it is more appropriate to assume that in the given context of the application we identify only certain variables and develop a set of causal relationships between them.

#### Bad Manipulation

Before discussing causation and the Markov condition, we note some cautionary procedures of which one must be aware when performing an **RCE**. First, we must be careful that we do not inadvertently disturb the system other than the disturbance done by manipulating the variable M itself. That is we must be careful we do not introduce more causal edges in the system being modeled.

***Example*** (*Bad Manipulation*):

Suppose we want to determine the relative effectiveness of home treatment and hospital treatment for low-risk pneumonia patients. Consider those patients of Dr X who are randomized for home treatment but whom should have been normally admitted to hospital. Dr X may give more instructions to such home-bound patients than he would give to the ***typical*** home bound patient. These instructions might influence patient outcomes. If those instructions are not measured, then the **RCE** may give biased estimates of the effect of the treatment location (home or hospital) on patient outcome. Note, we are interested in estimating the effect of treatment location on patient outcomes, everything else being equal. The **RCE** is actually telling us the effect of treatment allocation on patient outcomes, which is not of interest here. The manipulation of treatment location is a bad manipulation because it not only results in manipulation of treatment location but also has causal effect on physician’s other actions such as advice given. This is an example of what is called ***fat-hand manipulation*** in the sense that one wants to manipulate just one variable but one’s hand is so fat, so it ends up manipulating other variables.

Let us show with a DAG how this **RCE** inadvertently disturbs the system being modeled other than the disturbance done by itself. If we let L represent a treatment location, A represent treatment allocation and M represent the manipulation of treatment location.

Variable Value When the Variable Takes This Value

subject is at home

subject is at hospital

subject is allocated to be at home

subject is allocated to be at hospital

subject is chosen to stay home

subject is chosen to stay at the hospital

Other variables of the system:

– doctor’s evaluation of the patient

– doctor’s treatment

– patient outcome

Since the last 3 variables can have more than two values, we did not show them in the table above.

#### Causation and the Markov condition

Let us have a causal DAG (,). This means that given a set of variables , if there is an edge between and then is the direct cause of relative to . Then a manipulation of would change the probability distribution of in a such way that there would be no subset such that if we instantiate the variables in a manipulation of no longer changes the probability distribution of .

When constructing a causal DAG containing a set of variables V, we call V our ***set of observed variables***.

#### Why Causal DAGs Often Satisfy The Markov Condition

Let us consider the earlier example on company ’smanipulation study.

In this case the set of observed variables is . We do have a causal edge from to as it was shown on the Figure. We also do have causal edge from to . We suspect that influences only through so we did not place a causal edge from to .

If there is another causal path from to (i.e., affected by some means other than we would also place an edge from to as shown below.

Assuming the only causal connection between and is as indicated on the Figure it appears that and are conditionally independent given . This conditional independence holds because once we knew the value of we would have the probability distribution of based on this known value and since cannot change the known value of and there is no other connection between and it cannot change the probability distribution of . Manipulation experiments have substantiated this intuition. That is, there have been experiments in which it was established that causes , causes , and are not probabilistically independent and and are conditionally independent given .

***Theorem*** (*informal statement for Markov condition validity in causal DAGs*): In general, when all causal paths from to contain at least one variable in our set of observed variables , , and do not have common cause, there are no causal paths from back to , and we do not have selection bias then and are independent if we condition on a set of variables including at least one variable in each of the causal paths from to .

***Definition*** (*common cause*): we say that and have **common cause** if there is some variable that has causal paths into both and . If and have a common cause , there is often a dependency between them through that common cause. However, if we condition on ’s parent in the path from to , we can break this dependency for the same reasons discussed above. So as long as all common causes are in our set of observed variables , we can still break the dependency between and (assuming there are no causal paths from to ) by conditioning on the set of parents of , which means the Markov condition is still satisfied relative to and .

***Definition*** (*hidden variable*): A problem arises when at least one common cause is not in our set of observed variables . Such common cause is called hidden variable. If two variables had a hidden common cause, then there would often be a dependency between them, which the Markov condition would identify as independency. For example, consider the DAG shown below:

If we only identified the variables , and and causal relationships that and each caused , we would draw edges from each of and to . The Markov condition would entail and are independent. But if and had hidden common cause H, they would not ordinarily be independent. So, for us to assume the Markov condition is satisfied, either no two variables in the set of observed variables can have a hidden common cause, or, if they do, it must have the same unknown value for every unit in the population under consideration.

***Definition*** (*causally sufficient*): When the observed variables have a hidden common cause which impacts by the same unknown value every variable in the population, we say the observed variables are **causally sufficient**.

Another violation of the Markov condition, similar to the failure to include a hidden common cause is when there is a selection bias present.

***Definition*** (*selection bias*)

Let us consider again the earlier example on company ’smanipulation study. If the medication and apprehension that the test subject is using the medication both lead to (hypertension) and we are observing individuals hospitalized for hypertension we would observe probabilistic dependence between and due to **selection bias**. This is shown again on the figure below:

Note that in this situation our set of observed variables is . That is, is unobserved. So, if neither nor caused each other and they did not have hidden common cause a causal DAG containing only two variables (i.e., with no edges) would still not satisfy the Markov condition with the observed probability distribution because the Markov condition says and are independent when indeed they are not for this population.

Finally, we must make sure that if X has causal influence on Y, then Y does not have causal influence on X. In this way we guarantee that the identified causal edges will indeed yield a DAG. Causal feedback loops are discussed in [[Richardson and Sprites, 1999]](https://github.com/dimitarpg13/learning_bayesian_networks/blob/main/articles/AutomatedDiscoveryOfLinearFeedbackModelsRichardsonAndSprites1999.pdf).

One final remark, if we mistakenly draw an edge from X to Y in a case where X’s causal influence on Y is only through other variables in the model, we have not done anything to thwart the Markov condition being satisfied. For instance, consider again the Figure:

F ----- > D ------ > G

If ’s only influence on is through , we would not thwart the Markov’s condition by drawing an edge from to . That is, this does not result in the structure of DAG entailing any conditional dependencies which are not there. Instead, the opposite has happened – the DAG fails to entail conditional independency (namely ) that is there. This is violation of the *faithfulness condition*, not the *Markov condition*. In general, we would not want to do that because it makes the DAG less informative and unnecessarily increases the size of the instance which is important because the problem of doing Bayesian inference is NP-complete.

#### The Causal Markov Assumption

We’ve offered a definition of causation based on manipulation and we’ve argued that, given this definition of causation, a causal DAG often satisfies the Markov condition with the probability distribution of the variables which means we can construct a Bayesian network by creating a causal DAG.

***Definition*** (*causal Markov assumption*) we say we are making causal Markov assumption if we create causal DAG and assume that the probability distribution of the variables in satisfies the Markov condition with .



As discussed above, if the following three conditions are satisfied the causal Markov assumption is ordinarily warranted:

1. There must be no *hidden common causes*
2. Selection bias must not be present
3. There must be no causal feedback loops

In general, when constructing a Bayesian network using identified causal influences, one must take care that the causal Markov assumptions hold.

***Note***: We often identify causes using methods other than manipulation. For example, most of us believe smoking causes lung cancer. Yet, we have not manipulated individuals by making them smoke. We believe in this causal influence because smoking and lung cancer are correlated, the smoking precedes the cancer in time (common assumption is that an effect cannot precede the cause) and there are biochemical changes associated with smoking. All of this could possibly be explained by hidden common cause, but domain experts rule out this possibility. When we identify causes by any means our belief is that they can be identified by manipulation if we were to perform **RCE** and we make causal Markov assumption as long as we are confident that 1), 2) and 3) are not present.

***Example*** ( *cause identification based on elimination of 1), 2), and 3)* ):

Suppose we have identified the following causal influences by some means: history of smoking (H) has a causal effect both on bronchitis (B) and on lung cancer (L). Furthermore, each of these variables can cause a fatigue (F). Lunger Cancer (L) can cause positive chest X-Ray (C). Then the DAG on the Figure below represents our identified causal relationships among these variables. If we believe that:

1. These are the only causal influences among the variables
2. There are no hidden common causes
3. Selection bias is not present

it seems reasonable to make the causal Markov assumption.

#### The Markov Condition Without Causation

Using causal edges is just one way to develop a DAG and a probability distribution that satisfy the Markov condition. In a previous example we showed the joint distribution of V (value), S (shape), and C (color) satisfied the Markov condition with the DAG below, but we would not say that the color of an object has a causal influence on its shape. The Markov condition is simply a property of the probabilistic relationship between the variables. Furthermore, if the DAG on the Figure (a) below did capture the causal relationships among some causally sufficient set of variables and there was no selection bias present, the Markov condition would be satisfied not only in (a) but also in (b) and (c). Yes, we certainly would not say that the edges in (b) and (c) represent causal influence.

1. (b) (c)

V <------ C -------> S V ------> C -------> S V <------ C <------- S

***Example*** (*first Example on Markov condition satisfied by causal DAG*)

If Alice’s husband Ralph was planning a surprise birthday party for Alice with a caterer (), this may cause him to visit the caterer’s store (). The act of visiting that store would cause him to be seen () visiting that store. The causal relationships between the variables are like the ones depicted in Figure (a) below. There is no direct path from to because planning the party with the caterer could only cause him to be seen visiting the store *if it caused him to actually visit the store*. If Alice’s friend Trixie reported to her that she had seen Ralph visiting the caterer’s store today, Alice would conclude that he may be planning a surprise birthday party because she would feel there is a good chance Trixie really did see Ralph visiting the store, and in this case, there is a chance he maybe planning a surprise birthday party. So and are not independent. If, however, Alice has witnessed this same act of Ralph visiting the caterer’s store, she would already suspect Ralph may be planning surprise birthday party. Trixie’s testimony would not affect her belief concerning Ralph’s visiting the store and therefore would have no affect on her belief concerning his planning a party. So and are conditionally independent given as the Markov condition entails for the DAG on Figure (a). The instantiation of which renders and independent is depicted on Figure (b).

***Example*** (*second Example on Markov condition satisfied by causal DAG*)

A cold () can cause both sneezing () and runny nose (). Assume neither of these manifestations causes the other and, for a moment, also assume there are no hidden common causes (that is, the set of variables are causally sufficient). The causal relationships among the variables are then the ones depicted on the Figure a) below. Suppose now that Prof. P walks into the classroom with runny nose. You would fear she has cold, and, if so, the cold may make her sneeze. So, you back off from her to avoid the possible sneeze. We see then that and are not independent. Suppose next that Prof. P calls school in the morning to announce she has a cold which will make her late for class. When she finally does arrive, you back off immediately because you feel the cold may make her sneeze. If you see that her nose is running, this has no affect on your belief concerning her sneezing because the runny nose no longer makes the cold more probable. So, and conditionally independent given , as the Markov condition entails for the DAG in Figure (a) below. The instantiation of C is depicted in Figure (b) below.

There actually is at least one other common cause of sneezing and a runny nose, namely hay fever (H). Suppose this is the only common cause missing from the Figure (a) above. The causal relationships between the variables would then be as depicted in Figure (c) below. Given this, conditioning on is not sufficient to render and independent, because could still make more probable by making more probable. So, we must condition on both and to render and independent. The instantiation of and is depicted on Figure (d) below.

***Example*** (*third Example on Markov condition satisfied by causal DAG*)

A has observed that his burglar alarm (A) has sometimes gone off when a freight truck (F) was making a delivery to the Home Depot in the back of his house. So, he feels a freight truck can trigger the alarm. However, he also believes a burglar (B) can trigger the alarm. He does not feel that the appearance of a burglar might cause a freight truck to make a delivery or vice versa. Therefore, he feels that the causal relationships among the variables are the ones depicted on Figure (a) below:

Suppose A sees a freight truck making a delivery in back of his house. This does not make him feel a burglar is more probable. So, and are independent, as the Markov condition entails for the DAG on the Figure (a) above. Suppose next that A is awakened at night by the sound of his burglar alarm. This increases his belief that a burglar is present, and he begins fearing this is indeed the case. However, as he proceeds to investigate this possibility, he notices that a freight truck is making a delivery in back of his house. He reasons that this truck explains away the alarm, and therefore he believes a burglar probably is not present. Given the alarm has sounded, learning that a freight truck is present decreases the probability of a burglar. So, the instantiation of depicted on Figure (b) above, renders and conditionally dependent. As noted previously, the instantiation of a common effect creates a dependence between its causes because each explains away the occurrence of the effect, thereby making the other cause less likely.

Note that the Markov condition does not entail that and are conditionally dependent given . Indeed, a probability distribution can satisfy the Markov condition for a DAG without this conditional dependence occurring. Indeed, a probability distribution can satisfy the Markov condition without this conditional dependence occurring. However, if this conditional dependence does not occur, the distribution does not satisfy the faithfulness condition with the DAG.

## More DAG/Probability Relationships

We already discussed that the *Markov condition* entails independencies, and it does not entail any dependencies. That is, when we only know that satisfies the Markov condition, we know the absence of an edge between X and Y entails there is no direct dependency between X and Y, but the presence of an edge between X and Y does not mean there is a direct dependency. In general, we would want an edge to mean there is a direct dependency. We will discuss the *faithfulness condition* which entails that. The concept of faithfulness is essential to the methods for learning the structure of Bayesian networks from data. For some probability distributions it is not possible to find a DAG with which satisfies the faithfulness condition. We will present *minimality condition*, and we shall see that it is always possible to find a DAG such that satisfies the minimality condition. We will define and discuss *Markov blankets* and *Markov boundaries* which are sets of variables that render a given variable conditionally independent of all other variables. But first we will show that conditional independencies are entailed by the Markov condition. Then we will describe *Markov equivalence*, which groups DAGs into equivalence classes based on the conditional independencies they entail. The concept of Markov equivalence is necessary to the structure learning algorithms.

### Entailed Conditional Independencies

If satisfies the Markov condition, then each node in is conditionally independent of the set of all its nondescendents given its parents. Question we want an answer for: Do these conditional independencies entail any other conditional independencies? That is, if satisfies the Markov condition, are there any other conditional independencies which P must satisfy other than the one based on a node’s parents?

**Definition**. Let be a DAG, where is a set of random variables. We say that, based on the Markov condition, ***entails*** conditional independency for if

holds for every

where is the set of all probability distributions such that satisfies the Markov condition. We also say that the Markov condition entails the conditional independency for and that the conditional independency is ***in*** .

Note that the independency Is included in the previous definition because it is the same as . Regardless of whether C is the empty set, for brevity we often just refer to as an “independency” instead of a ‘conditional independency’.

*Examples of Entailed Conditional Independencies*

Suppose some distribution satisfies the Markov condition with the DAG in the Figure below. Then we know because is the parent of , and and are nondescendents of .

Furthermore, we know because is the parent of , and is a nondescendent of .

These are the only conditional independencies according to the statement of the Markov condition. However, can we conclude ? Let’s first give the variables meaning and the DAG a causal interpretation to see if we would expect this conditional independency.

Suppose we are investigating how professors obtain citations, and the variables represent the following:

: Graduate Program Quality

: First Job Quality

: Number of Publications

: Number of Citations

Further, suppose the DAG on the Figure above represents the causal relationships among these variables and there are no hidden common causes. Also, selection bias is not present. Then it is reasonable to make the causal Markov assumption, and we would feel the probability distribution of the variables satisfies the Markov condition with the DAG. Given all this, if we learned that Prof. L attended a graduate program of high quality (that is, we found out that the value of for Prof. L was ‘high quality’), we would expect his first job may well be of high quality, which means there should be a large number of publications, which in turn implies there should be a large number of citations. Therefore, we would not expect . If we learned that Prof. P’s first job was of the high quality (that is, we found out the value of for Prof. P was ‘high quality’), we would expect his number of publications to be large, and in turn his number of citations to be large. That is, we would also not expect .

If Prof. P then told us he attended a graduate program of high quality, would we expect the number of citations to be even higher than we previously thought? It seems not. The graduate program’s high quality implies the number of citations is probably large because it implies the first job is probably of high quality. Once we already know the first job is of high quality, the information on the graduate program should be irrelevant to our beliefs concerning the number of citations. Therefore we would expect to not only be conditionally independent of given its parent , but also its grandparent :

Either one seems to block the dependency between and that exists through the chain .

It is straightforward to show that the Markov condition does indeed entail for the DAG in the last Figure above. We illustrate this for the case where the variables are discrete. If satisfies the Markov condition,

.

Suppose we have an arbitrarily long directed linked list of variables and satisfies the Markov condition with that list. We can show that for any variable in the list, the set of variables above it are conditionally independent of the set of variables below it given that variable.

Suppose now that does not satisfy the Markov condition with the DAG on the last Figure above because there is a common cause of and . For the sake of illustration, let’s say represents the following in the current example:

: Ability.

Further suppose there are no other hidden common causes so that we would now expect P to satisfy the Markov condition with the DAG on the Figure below. Would we still expect ? It seems not. For example, suppose again that we initially learn Prof. P’s first job was of high quality. As before, we would feel it probable that he has a high number of citations. Then suppose we learn again that his graduate program was of high quality. Given the current model, this fact is indicative of his having high ability, which can affect his publication rate (and thereby his citation rate) directly. So we would not feel as we did with the previous model. However, if we knew the state of Prof. P’s ability, his attendance at a high quality graduate program could no longer be indicative of his ability, and therefore it would not affect our belief concerning his citation rate through the chain . Succinctly, we say that the chain *is blocked* *at* . So we would expect . Indeed, it is possible to prove the Markov condition entail for the DAG on the Figure below.

Figure: can be deduced from the Markov condition

Finally, consider the conditional independency . This independency is obtained directly by applying the Markov condition to the DAG on the last Figure above.

*Question*: Would be and still be independent if additionally to we also learn the state of ? That is, would we expect ?

Suppose we learn that Prof. G has a high publication rate (the value of ) and attended a high quality graduate program (the value of ). Then we later learned they also have high ability (the value of A). In this case their high ability could explain away their high publication rate, thereby making it less probable they had a high quality first job (aka *discounting* in the field of psychology). So the chain is opened by instantiating , and we would not expect . Note that the Markov condition does not entail dependency so we cannot say that the Markov condition entails .

Figure: the Markov condition does not entail

### separation

In the DAG shown in the first Figure of the previous section we showed that the Markov condition entails .

This conditional independency is an example of a DAG property called *d-separation*. That is, and are d-separated by in the DAG shown on the Figure:

In the development of the concept of d-separation we will show the following:

1 ) The Markov condition entails that all d-separations are conditional independencies

2 ) Every conditional independency entailed by the Markov condition is identified by d-separation.

That is, if satisfies the Markov condition, every d-separation in is a conditional independency in . Furthermore, every conditional independency, which is common to all probability distributions satisfying the Markov condition with , is identified by d-separation.

All d-separations are Conditional Independencies

Let us have a DAG , and a set of nodes , where , such that or for .

**Definition** The set of edges connecting are denoted as *a chain* between and . We denote the chain using any possible sequence between the nodes in the chain set. For example both the sequences and denoted the same chain.

On the graph shown below and represent the same chain between and .

Figure: Graph with multiple chains

Another chain between and is .

**Definition** The nodes are called *interior nodes* on the chain .

**Definition** The *subchain* of chain between and is the chain where .

**Definition** A *simple chain* is a chain which contains no cycles.

Alternative notation for a chain would be as illustrated by the example:

is denoted as or if we want to show the direction of the edges we use *.*

**Definition** A chain containing two nodes such as is denoted as *link*.

**Definition** An *edge* is a directed link, and it will be denoted as

**Definition** In an edge , will be denoted as the *tail* of the link and – the *head*.

**Definition** A chain is a *head-to-tail* *meeting*, the edges *meet head-to-tail* at , and is a *head-to-tail* *node* on the chain.

**Definition** A chain is a *tail-to-tail* meeting, the edges meet *tail-to-tail* at Z, and Z is a *tail-to-tail* node on the chain

Definition A chain is a head-to-head meeting, the edges meet head-to-head at Z, and Z is a head-to-head node on the chain.