Conditional Independence

CMPUT 366: Intelligent Systems

P&M §8.2

Lecture Outline

1. Recap
2. Structure
3. Marginal Independence
4. Conditional Independences

Recap: Probability

- **Probability** is a numerical measure of **uncertainty**
  - **Not** a measure of **truth**
- **Semantics:**
  - A **possible world** is a **complete assignment** of values to variables
  - Every possible world has a probability
  - Probability of a **proposition** is the sum of probabilities of **possible worlds** in which the statement is **true**

Recap:
Conditional Probability

- When we receive **evidence** in the form of a proposition e, it **rules out** all of the possible worlds in which e is **false**
  - We set those worlds' probability to **0**, and **rescale** remaining probabilities to sum to **1**
- Result is probabilities **conditional on e**: $P(h \mid e)$

Recap: Bayes' Rule

- From the **chain rule**, we have

$$\begin{aligned} P(h, e) &= P(h \mid e)P(e) \\ &= P(e \mid h)P(h) \end{aligned}$$

- **Often**, $P(e \mid h)$ is easier to compute than $P(h \mid e)$.

Bayes' Rule:

$$\overset{\text{Posterior}}{\boxed{P(h|e)}} = \frac{\overset{\text{Likelihood}}{\boxed{P(e|h)}}\,\overset{\text{Prior}}{\boxed{P(h)}}}{\underset{\text{Evidence}}{\boxed{P(e)}}}$$

Unstructured Joint Distributions

- Probabilities are not fully **arbitrary**
  - **Semantics** tell us probabilities given the joint distribution.
  - Semantics alone do not restrict probabilities **very much**
- In general, we might need to **explicitly** specify the entire **joint distribution**
  - **Question:** How many numbers do we need to assign to fully specify a joint distribution of k binary random variables?
- We call situations where we have to explicitly enumerate the entire joint distribution **unstructured**

Structure

- Unstructured domains are very hard to reason about
- Fortunately, most real problems are generated by some sort of **underlying process**
  - This gives us **structure** that we can exploit to represent and reason about probabilities in a more **compact** way
  - We can **compute** any required joint probabilities based on the process, instead of specifying every possible joint probability explicitly
- Simplest kind of structure is when random variables don't **interact**

Marginal Independence

When the value of one variable **never** gives you information about the value of the other, we say the two variables are **marginally independent.**

Definition:

Random variables X and Y are **marginally independent** iff

1. $P(X = x \mid Y = y) = P(X = x)$, and

2. $P(Y = y \mid X = x) = P(Y = y)$

for all values of $x \in dom(X)$ and $y \in dom(Y)$.

Marginal Independence Example

- I flip four **fair coins**, and get four results: C_1, C_2, C_3, C_4
- **Question:** What is the probability that C_1 is **heads**?
    - $P(C_1 = heads)$
- Suppose that C_2, C_3, and C_4 are **tails**
- **Question:** *Now* what is the probability that C_1 is **heads**?
    - $P(C_1 = heads \mid C_2 = tails, C_3 = tails, C_4 = tails)$
    - Why?

Properties of Marginal Independence

Proposition:

If X and Y are marginally independent, then

$$P(X = x, Y = y) = P(X = x)P(Y = y)$$

for all values of $x \in dom(X)$ and $y \in dom(Y)$.

Proof:

1. $P(X = x, Y = y) = \boxed{P(X = x \mid Y = y)}P(Y = y)$ Chain rule
2. $P(X = x, Y = y) = P(X = x)P(Y = y)$ Marginal independence

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Exploiting Marginal Independence

C_1	P
H	0.5

C_2	P
H	0.5

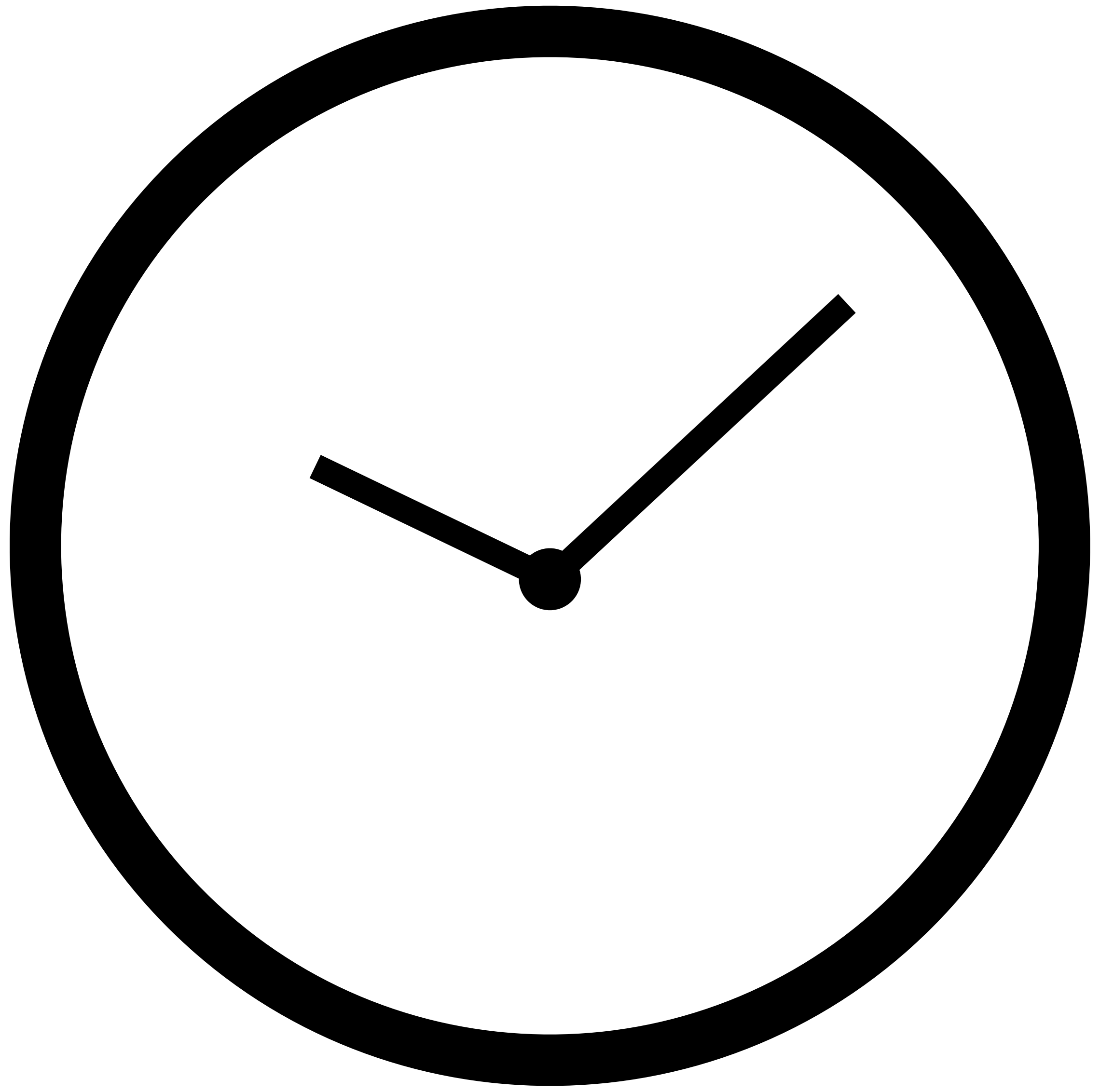
C_3	P
H	0.5

C_4	P
H	0.5

- Instead of storing the **entire joint distribution**, we can store 4 **marginal distributions**, and use them to recover joint probabilities
  - **Question:** How many numbers do we need to assign to fully specify the marginal distribution for a **single** binary variable?
- If **everything** is independent, learning from observations is hopeless
  - But also if **nothing** is independent
  - The **intermediate** case, where many variables are independent, is ideal

C_1	C_2	C_3	C_4	P
H	H	H	H	0.0625
H	H	H	T	0.0625
H	H	T	H	0.0625
H	H	T	T	0.0625
H	T	H	H	0.0625
H	T	H	T	0.0625
H	T	T	H	0.0625
H	T	T	T	0.0625
T	H	H	H	0.0625
T	H	H	T	0.0625
T	H	T	H	0.0625
T	H	T	T	0.0625
T	T	H	H	0.0625
T	T	H	T	0.0625
T	T	T	H	0.0625

Clock Scenario



Example:

- I have a stylish but impractical clock with no number markings
- Two students, Alice and Bob, both look at the clock at the same time, and form opinions about what time it is
  - They are likely to be *close* to the **real time**, but a *little bit off*
- **Question:** Are A and B marginally **independent**?

$$P(A \mid B) \neq P(A)$$

- **Question:** Suppose it is 10:09. Are A and B **independent**?

$$P(A \mid B, T = 10:09) = P(A \mid T = 10:09)$$

Random variables:

A - Time Alice thinks it is

B - Time Bob thinks it is

T - Actual time

Conditional Independence

When knowing the value of a **third** variable Z **makes** two variables A, B independent, we say that they are **conditionally independent given** Z (or **independent conditional on** Z).

Definition:
Random variables X and Y are **conditionally independent given *Z*** iff

$$P(X = x \mid Y = y, Z = z) = P(X = X \mid Z = z)$$

for all values of $x \in dom(X)$, $y \in dom(Y)$, and $z \in dom(Z)$.
We write this using the notation $X \perp\!\!\!\perp Y \mid Z$.

Clock example: A and B are conditionally independent given T.

Properties of Conditional Independence

Proposition:

If X and Y are conditionally independent given Z, then

$$P(X = x, Y = y \mid Z) = P(X = x \mid Z)P(Y = y \mid Z)$$

for all values of $x \in dom(X)$, $y \in dom(Y)$, and $z \in dom(Z)$.

Proof:

1. $P(X = x, Y = y \mid Z) = \boxed{P(X = x \mid Y = y, Z = z)}P(Y = y \mid Z)$ Chain rule
2. $P(X = x, Y = y \mid Z) = P(X = x \mid Z)P(Y = y \mid Z)$ Conditional independence

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Properties of Conditional Independence

Question: Is conditional independence **commutative**?

- i.e., If $X \perp\!\!\!\perp Y \mid Z$, is it also true that $Y \perp\!\!\!\perp X \mid Z$?

Proof:

$$X \perp\!\!\!\perp Y \mid Z \iff P(X, Y \mid Z) = P(X \mid Z)P(Y \mid Z)$$

$$\iff P(Y, X \mid Z) = P(Y \mid Z)P(X \mid Z)$$

Exploiting Conditional Independence

If X and Y are marginally independent given Z, then we can again just store **smaller tables** and recover joint distributions by **multiplication.**

- **Question:** How many **tables** do we need to store in order to be able to compute the joint distribution of X, Y, Z when X and Y are independent given Z?

Caveats

- Often, when two variables are **marginally** independent, they are also **conditionally** independent given a third variable
  - E.g., coins C_1, and C_2 are marginally independent, **and also** conditionally independent given C_3: Learning the value of C_3 does not make C_2 any more informative about C_1.
- This is **not always true**
  - Consider another random variable: B is true if both C_1 and C_2 are the **same** value
  - C_1 and C_2 are **marginally independent**: $P(C_1 = heads \mid C_2 = heads) = P(C_1 = heads)$
    - In fact, C_1 and C_2 are also both **marginally independent of *B***: $P(C_1 \mid B = true) = P(C_1)$
  - But if I know the value of B, then knowing the value of C_1 tells me **exactly** what the value of C_2 must be: $P(C_1 = heads \mid B = true, C_2 = heads) \neq P(C_1 = heads \mid B = true)$
    - C_1 and C_2 are **not conditionally independent given *B***

Summary

- **Unstructured** joint distributions are **exponentially** expensive to represent (and operate on)
- **Marginal and conditional independence** are especially important forms of **structure** that a distribution can have
  - Vastly **reduces the cost** of representation and computation
  - **Caveat:** The **relationship** between marginal and conditional independence is not fixed
- Joint probabilities of (conditionally or marginally) **independent** random variables can be computed by **multiplication**