

Graphical Markov Models

3 Lectures

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- 1 Conditional independence
Graphs (DAG, UG, BG, RCG)
Markov Properties
Conditional Indep. tests
Examples
- 2 Undirected graphs.
Markov properties
Separation, decomposable graphs
Fitting by ML, Examples
- 3 Bidirected graphs
Regression chain graphs
Markov properties
Parametrizations
Fitting graphs to data
Examples

LECTURE 1

Summary

- Conditional independence
- Properties
- Graphical Markov Models

Directed acyclic graphs

Undirected graphs

Regression graphs

References

- Højsgaard, Edwards, Lauritzen (2012) Graphical Models in R, Springer V.
- Scutari', Denis (2022) Bayesian Networks CRC Press.
- Cox, Wermuth (1996) Multivariate dependencies, Chapman & Hall.
- Roverato (2017) Graphical models for categorical variables.
- Whittaker (1990) Graphical models in applied multivariate statistics Wiley.

Useful R packages

• bnlearn (Scutari et al.)

gRbase (Højsgaard et al)
gRim

ggm (Marchetti et al)

cct (J. Lang)

Look at the CRAN Task View

→ <https://CRAN.R-project.org/view=GraphicalModels>

Other References.

J. Pearl et al (2016) Causal Inference in Statistics. Wiley.

Hernán, Robins (2020). What if. CRC Press.

Look at the CRAN Task View

→ <https://cran.r-project.org/web/views/CausalInference.html>

Data

We will consider a system of d variables

$$\underline{x} = (x_1, x_2, x_3, \dots, x_d)$$

can be

- continuous (Gaussian)
- categorical or binary.
- mixed

Example

→ Gaussian $\underline{x} \sim N(\underline{\mu}, \Sigma)$

→ Multinomial $\underline{x} \sim \text{Mult}(n, \pi)$

Exercise 1

Simulate 1000 observations
from 3 binary variables

x_1, x_2, x_3 with a joint prob.

$$\pi = (0.38, 0.01, 0.07, 0.01, \\ 0.42, 0.02, 0.08, 0.01)$$

Exercise 2

Simulate 100 observations
from $N_3(\underline{\mu}, \Sigma)$ with

$$\Sigma^{-1} = \begin{bmatrix} 1.2 & 0.9 & 0 \\ 2.7 & 1.4 & \\ 1.6 & & \end{bmatrix}$$

Solutions

Exercise 1

8 

```
n = 1000
p <- c(0.38, 0.01, 0.07, 0.01,
      0.42, 0.02, 0.08, 0.01)
X<- expand.grid(X1 = factor(0:1),
                  X2 = factor(0:1),
                  X3 = factor(0:1))
Z <- rmultinom(n, size = 1, prob = p)
cell <- apply(Z, 2, function(x) which(x==1))
data <- X[cell,]
rownames(data) <- 1:n

head(data)
tail(data)

table(data)
as.data.frame(table(data))
```

$\pi \sim \text{Dir}(0, 0, 0, 0)$

0 0 0
1 0 0
0 1 0
1 1 0
0 0 1
1 0 1
0 1 1
1 1 1

Exercise 2

```
library(mnormt)
K <- matrix(c(1.2, 0.9, 0,
              0.9, 2.7, 1.4,
              0, 1.4, 1.6), 3, 3)
dimnames(K) <- list(c("X1", "X2", "X3"),
                      c("X1", "X2", "X3"))
Sigma <- solve(K)
dimnames(Sigma) <- list(c("X1", "X2", "X3"),
                         c("X1", "X2", "X3"))
round(Sigma, 2)
round(cov2cor(Sigma), 2)
X <- rmnorm(n = 100, varcov = Sigma)
```

Conditional independence

Random vector (X_1, \dots, X_d) ↗ all contim.
↗ all discrete

Denote the joint distribution by

$$p_V(x_1, \dots, x_d) \xrightarrow{\text{pmf}} \text{pmf}$$

where

$$V = \{1, 2, \dots, d\}$$

Example

$$\text{If } (X_1, X_2) \quad p_{12}(x_1, x_2)$$

Conditional Distributions

$$X_1 | X_2 \quad P_{1|2}(x_1 | x_2)$$

$$X_1 | X_2, X_3 \quad P_{1|23}(x_1 | x_2, x_3)$$

Conditional independence

Given 3 variables X_1, X_2, X_3

X_1 conditionally independent of X_2
given X_3

if

$$P_{12|3}(x_1, x_2 | x_3) = P_{1|3}(x_1 | x_3) P_{2|3}(x_2 | x_3)$$

for all (x_1, x_2, x_3) such that $P_3(x_3) > 0$

Properties of CI

Notation $X_1 \perp\!\!\!\perp X_2 \mid X_3$

abbreviated $1 \perp\!\!\!\perp 2 \mid 3$

Equivalent (omit the suffix)

$$P(x_1 | x_2 x_3) = P(x_1 | x_3) \quad P(x_2, x_3) > 0$$

Factorizations

$$\begin{aligned} p(x_1, x_2, x_3) &= p(x_1 | x_3) p(x_2 | x_3) p(x_3) - \\ &= p(x_1 | x_3) p(x_3 | x_2) p(x_2) - \end{aligned}$$

Marginal independence

$$X_1 \perp\!\!\!\perp X_2 \text{ if } P_{12}(x_1, x_2) = P_1(x_1) P_2(x_2)$$

for all x_1, x_2 .

It's a quite different constraint.

Exercise 3

Two binary variables have marginal probabilities

$$P_1(x_1) = \{0.2, 0.8\} \quad P_2(x_2) = \{0.6, 0.4\}$$

and odds-ratio = 1 odr = $\frac{\pi_{11}}{\pi_{12}} \frac{\pi_{22}}{\pi_{21}}$

What is the joint distribution?

Exercise 4

Does $X_1 \perp\!\!\!\perp X_2 \Rightarrow X_1 \perp\!\!\!\perp X_2 | X_3$?

Does $X_1 \perp\!\!\!\perp X_2 | X_3 \Rightarrow X_1 \perp\!\!\!\perp X_2$?

Solutions

Exercise 3

$$\text{odr} = 1 \iff X_1 \perp\!\!\!\perp X_2$$

Thus, $P_{12}(x_1, x_2) =$

0.12	0.2
0.8	
0.6 0.4	

Exercise 4

Counterexample 1

		$x_3 = 1$	
		0	1
x_1	x_2	0	37 8
		1	3 2

$$\text{odr} = 3.08$$

		$x_3 = 2$	
		0	1
x_1	x_2	0	9 38
		1	1 2

$$\text{odr} = 0.47$$

		Marginal X_1, X_2	
		0	1
x_1	x_2	0	46 46
		1	4 4

$$\text{odr} = 1$$

Counterexample 2

		$x_3 = 0$	
		0	1
x_1	x_2	0	384 96
		1	16 4

$$\text{odr} = 1$$

		$x_3 = 1$	
		0	1
x_1	x_2	0	40 360
		1	10 90

$$\text{odr} = 1$$

424 456
26 94

$$\text{odr} = 3.36$$

$X_1 \perp\!\!\!\perp X_2 \mid X_3$

A fundamental property of CI

Let $d=4$ (X_1, X_2, X_3, X_4) and consider the joint (conditional) indep.

$$X_1 \perp\!\!\!\perp X_2 X_3 \mid X_4 \quad 1 \perp\!\!\!\perp 23 \mid 4$$

1

Proposition

$$1 \perp\!\!\!\perp 23 \mid 4 \iff$$

$$1 \perp\!\!\!\perp 2 \mid 4$$

and

$$1 \perp\!\!\!\perp 3 \mid 24$$

This property makes it possible to decompose a CI involving random vectors into a set of pairwise CIs

Semigraphoids

look at

Pearl, Judea. 1988. Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. San Mateo, CA: Morgan Kaufmann.

Further properties

- Intersection
- Composition ... later on

Concentration matrix

Let $\underline{X} = (X_1, \dots, X_d)$ be a Gaussian r.v.

Its covariance matrix is

$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \dots & \sigma_{1d} \\ \vdots & \sigma_{22} & \dots & \sigma_{2d} \\ & \ddots & & \sigma_{dd} \end{bmatrix} > 0$$

Its concentration matrix is

$$K = \Sigma^{-1} = \begin{bmatrix} K_{11} & K_{12} & \dots & K_{1d} \\ & K_{22} & \dots & K_{2d} \\ & \ddots & & K_{dd} \end{bmatrix} > 0$$

Block covariance matrix

Sometimes we consider a partition of the variables. Example

$$V = \{1, 2, 3, 4, 5\} \quad a = \{1, 2\} \quad b = \{3, 4, 5\}$$

$$\underline{X} = (X_a, X_b)$$

$$\Sigma = \begin{pmatrix} \Sigma_{aa} & \Sigma_{ab} \\ & \Sigma_{bb} \end{pmatrix} \quad K = \Sigma^{-1} = \begin{pmatrix} K_{aa} & K_{ab} \\ & K_{bb} \end{pmatrix}$$

$$K_{aa} \neq \Sigma_{aa}^{-1}$$

$$K_{aa} = (\Sigma_{aa} - \Sigma_{ab} \Sigma_{bb}^{-1} \Sigma_{ba})^{-1}$$

Conditional independence
in Gaussian distributions.

Let $\underline{X} = (X_1, \dots, X_d) \sim N_d(\underline{\mu}, \Sigma)$

Well-known $X_1 \perp\!\!\!\perp X_2 \iff \sigma_{12} = 0$

When $X_1 \perp\!\!\!\perp X_2 | X_3$?

① Conditional covariance $\text{cov}(X_1, X_2 | X_3) = 0$

$$\sigma_{12} - \sigma_{13} \sigma_{32} / \sigma_{33} = 0$$

② Conditional regression coefficient $\beta_{12} = 0$

$X_1 | X_2, X_3 \sim N(E(X_1 | X_2, X_3), \text{var}(X_1 | X_2, X_3))$

$$\begin{aligned} & \text{linear} \leftarrow & \text{constant} \leftarrow \\ & \beta_{12} X_2 + \beta_{13} X_3 & \downarrow \\ & \sim \frac{\kappa_{12}}{\kappa_{11}} & \sim \frac{\kappa_{13}}{\kappa_{11}} & \frac{1}{\kappa_{11}} \end{aligned}$$

$$X_1 \perp\!\!\!\perp X_2 | X_3 \iff E(X_1 | X_2, X_3) = \beta_{13} X_3$$

$$\iff \beta_{12} = 0$$

$$\iff \kappa_{12} = 0$$

Graphical models

It is useful to regard conditional indep. as expressing the notion of *irrelevance*

$$X \perp\!\!\!\perp Y \mid Z$$

if we know Z , information about Y is irrelevant for knowledge of X

$$X \perp\!\!\!\perp Y$$

if we ignore all other variables
 Y looks irrelevant for X

Irrelevance



separation

Relevance



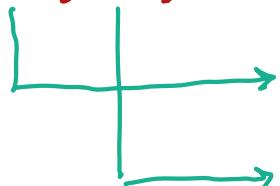
connection



Idea: use graphs to represent a set of conditional or marginal ind. expressed by separation

Graphs

$$G = (V, E)$$

 nodes = {1, 2, ..., d}
edges connecting
two nodes (i, j)

Edges: arrows $i \rightarrow j$

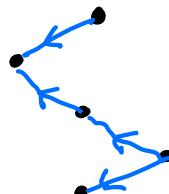
full lines $i - j$

arcs $i \leftrightarrow j$

Types of graph

Directed acyclic DAG

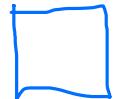
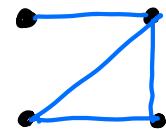
only arrows — no cycles



Undirected

UG

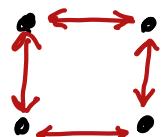
only full lines



Bidirected

BG

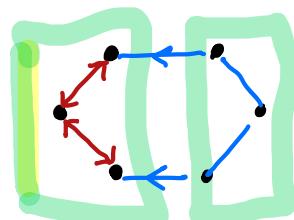
only bi-directed edges



Mixed

MG

All three types of edge

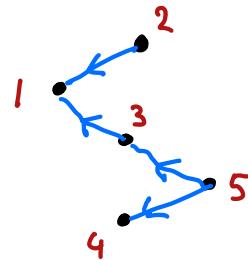


require(ggm)

Define graphs in ggm

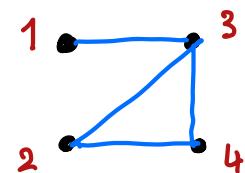
DAG($X_1 \sim X_2 + X_3$, $X_3 \sim X_5$, $X_4 \sim X_5$)

	X_1	X_2	X_3	X_5	X_4
X_1	0	0	0	0	0
X_2	1	0	0	0	0
X_3	1	0	0	0	0
X_5	0	0	1	0	1
X_4	0	0	0	0	0



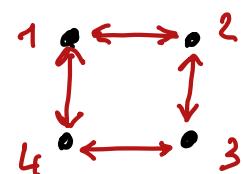
UG($\sim X_1 \cdot X_3 + X_2 \cdot X_3 \cdot X_4$)

	X_1	X_3	X_2	X_4
X_1	0	1	0	0
X_3	1	0	1	1
X_2	0	1	0	1
X_4	0	1	1	0



100 * UG($\sim X_1 \cdot X_2 + X_2 \cdot X_3 + X_3 \cdot X_4 + X_1 \cdot X_4$)

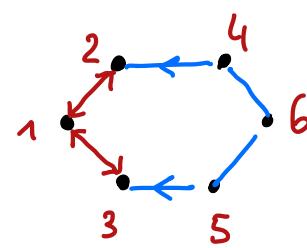
	X_1	X_2	X_3	X_4
X_1	0	100	0	100
X_2	100	0	100	0
X_3	0	100	0	100
X_4	100	0	100	0



```

makeMG(bg = UG(~ X1*X2 + X1*X3),
       dg = DAG(X2 ~ X4, X3 ~ X5),
       ug = UG(~ X4*X6 + X5*X6))
  
```

	X_2	X_4	X_3	X_5	X_6	X_1
X_2	0	0	0	0	0	100
X_4	1	0	0	0	10	0
X_3	0	0	0	0	0	100
X_5	0	0	1	0	10	0
X_6	0	10	0	10	0	0
X_1	100	0	100	0	0	0



Directed acyclic graph models.

Example from German labor market

A, suc- cessful job placem.	B, field of qualification			
	home economics		mechan. engineering	
	C, gender		C, gender	
female	male	female	male	
yes	15 (3.61%)	2	4 (20.0%)	95 (21.1%)
no	400	53	16	355
sum	415	55	20	450
odds-ratio	0.99		0.93	

A : successful job placement response

B : Field of qualification intermediate

C : Gender context variable

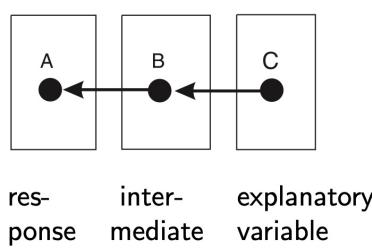
A depends on B and C

B depends on C (both explanatory and response)

C is an intrinsic v.

Data show a CI : $A \perp\!\!\!\perp C | B$

Graph :



The missing edge $A \leftarrow C$ implies a CI

Exercise

What happens if we ignore
 $B = \text{Field of qualification}$?

Find the marginal distribution
of A and C and the odds-ratio



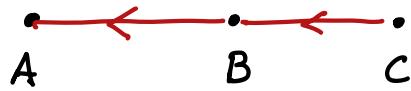
What's the interpretation ?

Solution

Discrimination against women?

A, successful job placement	C, gender	
	female	male
yes	19 (4.4%)	97 (19.2%)
no	416	408
sum	435	505
odds-ratio	0.19	

Factorization according to a DAG



The **parents** of a node i are the nodes that are directly connected to i .

$$pa(A) = \{B\}$$

$$pa(B) = \{C\}$$

$$pa(C) = \emptyset$$

The joint distribution of (A, B, C) can be factorized recursively

$$P(a, b, c) = P(a|bc) P(b|c) P(c)$$

and it simplifies if there are independencies

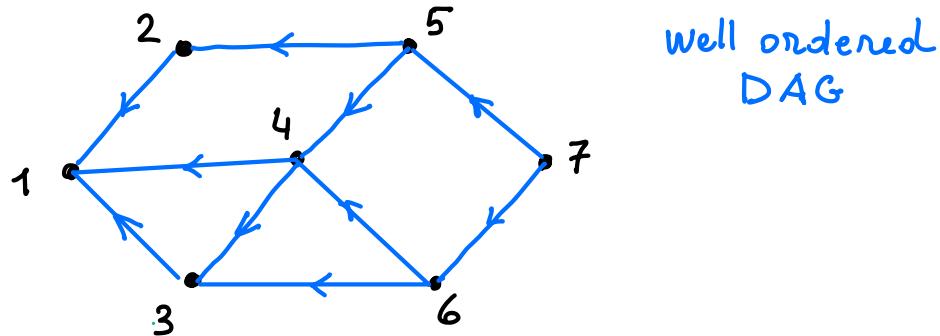
$$P(a, b, c) = P(a|b) P(b|c) P(c) \quad P \not\subseteq | \not\in$$

\downarrow \downarrow \downarrow
 $pa(A)$ $pa(B)$ $pa(C)$

General formula

$$\begin{aligned}
 P(x_1, x_2, \dots, x_d) &= P(x_1 | pa(x_1)) \times \\
 &\quad P(x_2 | pa(x_2)) \times \\
 &\quad \vdots \\
 &\quad P(x_d) \\
 &= \prod_{i=1}^d P(x_i | pa(x_i)).
 \end{aligned}$$

Exercise



well ordered DAG

Find the recursive factorization.

Solution

$$\begin{aligned} P(x_1, \dots, x_7) = & P(x_1 | x_2, x_3, x_4) \times \\ & P(x_2 | x_5) \times \\ & P(x_3 | x_4, x_6) \times \\ & P(x_4 | x_5, x_6) \times \\ & P(x_5 | x_7) \times \\ & P(x_6 | x_7) P(x_7). \end{aligned}$$

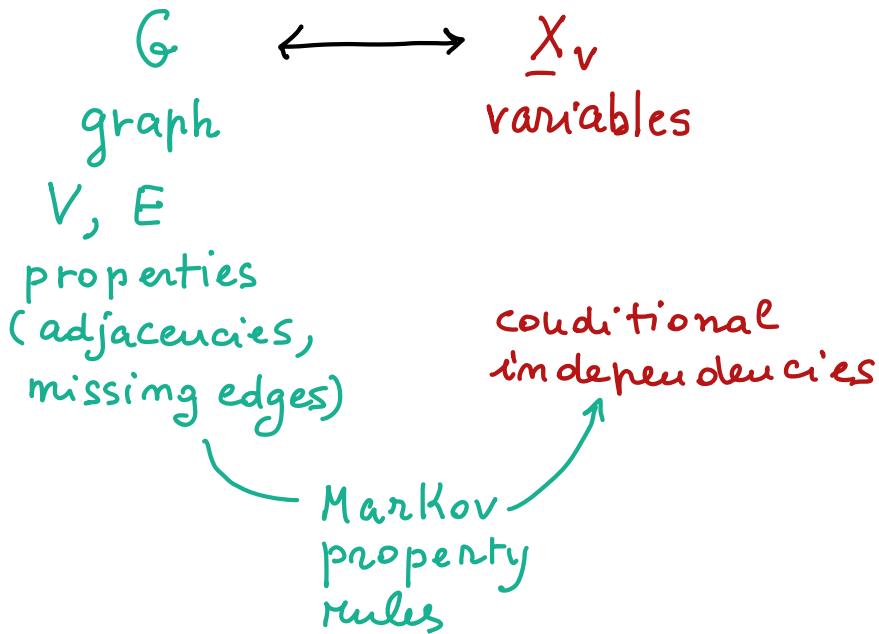
Exercise

Which independencies are present ?

Solution

$$\begin{aligned} X_1 \perp\!\!\!\perp & X_5 X_6 X_7 | X_2 X_3 X_4 \\ X_2 \perp\!\!\!\perp & X_3 X_4 X_6 X_7 | X_5 \\ X_3 \perp\!\!\!\perp & X_5 X_7 | X_4 X_6 \\ X_4 \perp\!\!\!\perp & X_7 | X_5 X_6 \\ X_5 \perp\!\!\!\perp & X_6 | X_7 \end{aligned}$$

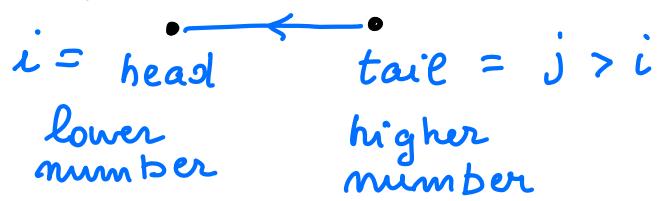
Markov property.



Specifies the rules that translate the properties of the graph into conditional independencies

Ordered Markov property for DAGs

Every DAG can be well-ordered so that given two nodes



The predecessors of a node : $\text{pre}(i)$ are the set of nodes j that are $> i$

Then the rule is :

$$\rightarrow X_i \perp\!\!\!\perp X_{\text{pre}(i) \setminus \text{pa}(i)} \mid X_{\text{pa}(i)}$$

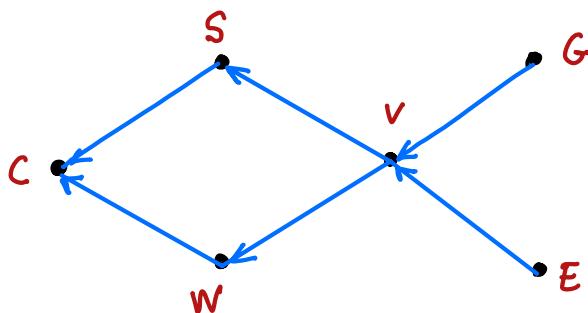
Simulated
(Scutari et al.)

Example: cropdata

In the analysis of a specific plant
a simple model is

C: crop (grain mass)	S: number of seeds W: seeds weight	V: Vegetative organs	G: genetic potential E: environm. potential
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A DAG model shows a generating process.



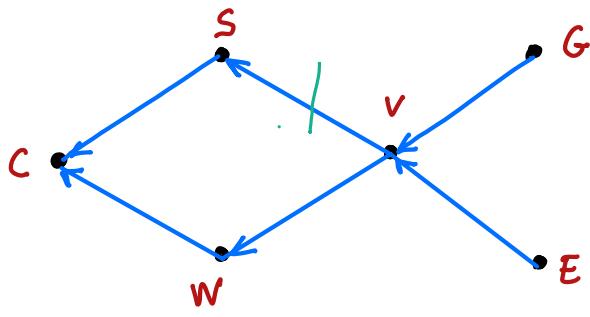
Assume that the joint p is Gaussian

Factorization:

$$P = P_{C|SW} \times P_{S|V} \times P_{W|V} \times P_{V|GE} \times P_G \times P_E$$

All the factors are univariate
conditional normal distributions

Recursive univariate regression models



Order :
 C
 S
 W
 V
 G
 E

Simulation

$n = 200$

$$C|SW \sim N(0.3S + 0.3W; 6.25^2)$$

$$S|V \sim N(45 + 0.1V; 9.94^2)$$

$$W|V \sim N(15 + 0.7V; 7.14^2)$$

$$V|GE \sim N(-10.3 + 0.5G + 0.77E; 5^2)$$

$$G|E \sim N(50; 10^2)$$

$$E \sim N(50; 10^2)$$



Exercise

Parameters, variation independence

Each density depends on 2 parameters

- β regression coefficients
- σ^2 conditional variance

The parameter space of the model is the Cartesian product of the separate ranges of its components

Model fitting.

- Maximum likelihood estimation
- Done by separate fit of each regression model.

```
m_full <- lm(C ~ S+W+V+G+E, data = crop)
```

FIRST EQUATION

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.001	4.349	0.000	
S	0.276	0.047	5.838	0.000
W	0.706	0.067	10.606	0.000
V	-0.098	0.098	-0.997	0.320
G	0.078	0.062	1.275	0.204
E	0.043	0.079	0.552	0.581

```
m_red <- lm(C ~ S + W, data = crop)
anova(m_red, m_full, test = "F")
```

Model 1: C ~ S + W

Model 2: C ~ S + W + V + G + E

	Res.Df	RSS	Df	Sum of Sq	F	Pr(>F)
1	197	7851.9				
2	194	7770.3	3	81.565	0.6788	0.566

LRT

w	df	p
2.0884556	3.0000000	0.5542518

C || VGE | SW

```
m_full <- lm(S ~ W + V + G + E, data = crop)
```

SECOND EQUATION

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	54.374	5.313	10.235	0.000
W	0.020	0.101	0.199	0.842
V	0.014	0.148	0.097	0.923
G	-0.081	0.093	-0.874	0.383
E	-0.048	0.119	-0.402	0.688

LRT

```
m_red <- lm(S ~ 1, data = crop)
```

w	df	p
0.8098683	3.0000000	0.8471052

S || WGE | v

w	df	p
1.2909126	4.0000000	0.8629154

S || WVGE

(continued)

```
m_full <- lm(W ~ V + G + E, data = crop)
```

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	18.702	3.518	5.317	0.000
V	0.593	0.096	6.168	0.000
G	0.062	0.066	0.947	0.345
E	-0.035	0.084	-0.420	0.675

w	df	p
2.2415432	2.0000000	0.3260281

THIRD
EQUATION

LRT

WILGE / V

```
m_full <- lm(V ~ G + E, data = crop)
```

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-10.455	2.500	-4.182	0
G	0.455	0.036	12.501	0
E	0.743	0.033	22.357	0

4th
EQUATION

no
independence

```
m_full <- lm(G ~ E, data = crop)
```

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	49.692	3.365	14.766	0.000
E	0.009	0.065	0.137	0.891

5th
EQUATION

```
m_red <- lm(G ~ 1, data = crop)
```

w	df	p
0.01905948	1.0000000	0.89019611

LRT

GLE

Overall fit using ggm

```
G <- DAG(C ~ S + W, S ~ V, W ~ V, V ~ G + E)
G
  C S W V G E
C 0 0 0 0 0 0
S 1 0 0 0 0 0
W 1 0 0 0 0 0
V 0 1 1 0 0 0
G 0 0 0 1 0 0
E 0 0 0 1 0 0
```

Adjacency matrix

```
ord <- colnames(G)
S <- cov(crop[,ord])
fitDag(G, S, n = 200)
```

covariance matrix

in the same order of data

Fit the DAG

\$Shat

	C	S	W	V	G	E
C	84.539	22.814	56.638	42.640	17.156	33.639
S	22.814	90.605	-2.860	-4.848	-1.950	-3.824
W	56.638	-2.860	83.725	64.107	25.792	50.574
V	42.640	-4.848	64.107	108.656	43.716	85.719
G	17.156	-1.950	25.792	43.716	96.019	0.000
E	33.639	-3.824	50.574	85.719	0.000	115.416

fitted covariance matrix

\$Ahat

	C	S	W	V	G	E
C	1	-0.273	-0.686	0.000	0.000	0.000
S	0	1.000	0.000	0.045	0.000	0.000
W	0	0.000	1.000	-0.590	0.000	0.000
V	0	0.000	0.000	1.000	-0.455	-0.743
G	0	0.000	0.000	0.000	1.000	0.000
E	0	0.000	0.000	0.000	0.000	1.000

fitted reg. coeff with sign change of

\$Dhat

C	S	W	V	G	E
39.457	90.388	45.902	25.090	96.019	115.416

partial variances

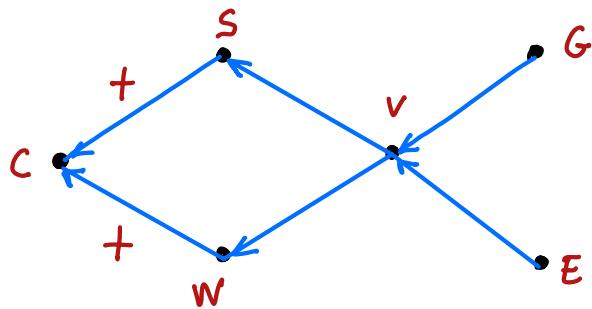
\$dev
[1] 5.159

deviance

\$df
[1] 9

dL.f.

Separation in DAGs and its connection with Conditional independence



We derived some CI from this graph
however

what can you say about $S \perp\!\!\!\perp W | C$?

It depends on $\rho_{Sw|c} = 0$ or $P_{Sw|c} = 0$

We can estimate it from data :

$$\hat{P}_{Sw|c} = -0.28$$

Or test it from data

```
ci.test("S", "W", "C", data = crop)
```

```
cor = -0.2876, df = 197, p-value = 3.808e-05
```

used.
← bnlearn
Reject
 $H_0: S \perp\!\!\!\perp W | C$

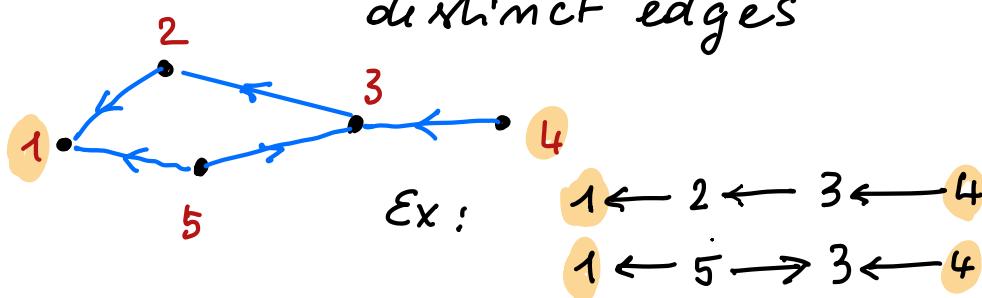
Can we say something without data ?

d -separation in DAGs

It is possible to use d -separation to answer to any CI statement

$$A \perp\!\!\!\perp B \mid C \quad \text{for any triple of subsets of } V$$

Paths in DAG: a sequence of consecutive distinct edges



Blocked paths: by a set of nodes C iff

- the path contains a **chain** $\rightarrow m \rightarrow$ or a **fork** $\leftarrow m \rightarrow$
such that m is in C
- or the path contains a **collider** $\rightarrow m \leftarrow$
such that m is not in C and
no descendants of m are in C

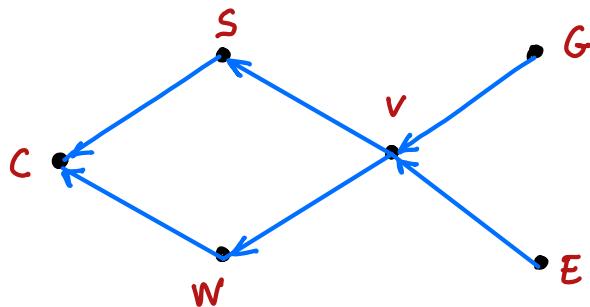
Two subsets of nodes A and B are said d -separated given C if every path between A and B is blocked by C

Global Markov Property in DAGs

Pearl 1988

Given a DAG, if $A, B, C \subset V$ are disjoint, and A and B are d-separated given C then $A \perp\!\!\!\perp B | C$

Example



$S \perp\!\!\!\perp W | C$? NO because the path $S \rightarrow C \leftarrow W$ contains a collider node C that is inside the conditioning set.

$S \perp\!\!\!\perp W | VG$? YES Paths

$S \rightarrow C \leftarrow W$ C not in VG
 $S \leftarrow V \rightarrow W$ V is in VG

```
> dSep(G, "S", "W", "C")
[1] FALSE
```

```
> dSep(G, "S", "W", c("V", "G"))
[1] TRUE
```

} check
using R package
ggm

$G \perp\!\!\!\perp E | S$? Exercise

Fit DAG models with categorical data

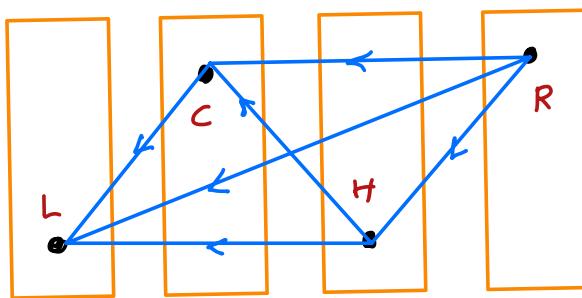
Canadian Women Labour Force participation

Data on 263 married women ages 21-30 (1977)

	R	Atlantic	BC	Ontario	Prairie	Quebec		
H	0	0	0	1	4	6	0	5
C	1		1	4	11	3	10	
L	1	0	11	6	25	15	18	
R	1		2	0	4	4	4	
H	1	0	0	1	4	6	1	5
C	1		1	2	10	1	3	
L	1	0	11	8	44	7	19	
R	1		2	1	2	0	1	

L Full time work
 C Presence of children
 H Husband's income (1 = \geq median \$14000)
 R Region

Ordering of the variables
(L, C, H, R)



Multinomial model (cross-classified)

$2 \times 2 \times 2 \times 5$ Table

$$\pi_{\text{echr}} = \tilde{\pi}_{e|\text{chr}} \tilde{\pi}_{c|\text{hr}} \tilde{\pi}_{h|\text{r}} \tilde{\pi}_{\text{r}}$$

Logistic regression

$$L \mid C H R \quad \pi_{\text{Lchr}} = P(L=1 \mid c, h, r)$$

$$\text{logit}(\pi) = \log \frac{\pi}{1-\pi} \quad (0,1) \mapsto (-\infty, +\infty)$$

generalized linear model

$$\begin{array}{l} \rightarrow L \sim C + H + R \quad (\text{link} = \text{logit}) \\ \rightarrow L \sim C * H * R \quad (\text{link} = \text{logit}) \end{array}$$

choose selected interactions!

```
glm(L ~ C + H + R, family = binomial, data =
wlfdata)
```

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	1.041	0.607	1.715	0.086
C1	-2.609	0.361	-7.234	0.000
H1	-0.768	0.348	-2.210	0.027
RBC	-0.944	0.745	-1.266	0.206
ROntario	-0.254	0.590	-0.430	0.667
RPrarie	0.168	0.695	0.241	0.809
RQuebec	-0.342	0.627	-0.545	0.586

```
glm(L ~ C + H, family = binomial, data = wlfdata)
```

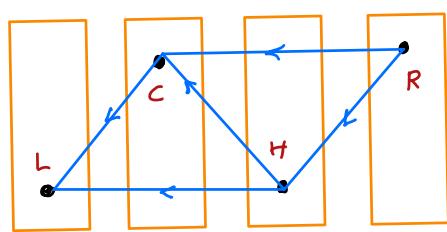
w	df	p
2.8117211	4.0000000	<u>0.5898111</u>

LRT test of

$L \perp\!\!\!\perp R \mid CH$

+ non-independence constraints.

The constraints
are not visible
in the graph



Recursive logistic model

$C | H | R$ generalized linear model

$$C \sim H + R \quad (\text{link} = \text{logit})$$

(interaction not significant)

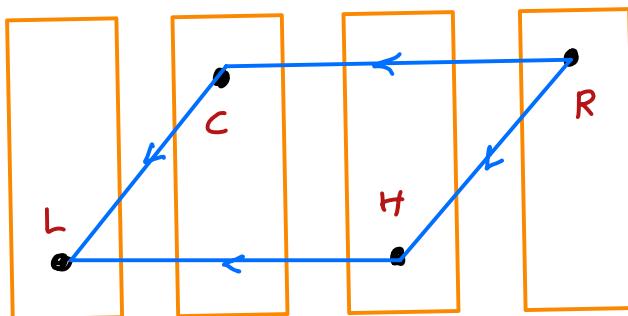
```
glm(C ~ H + R, family = binomial, data = wlfdata)
```

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	1.671	0.551	3.030	0.002
H1	0.437	0.282	1.546	0.122
RBC	-1.827	0.656	-2.785	0.005
ROntario	-1.092	0.579	-1.886	0.059
RPrarie	-0.136	0.730	-0.186	0.852
RQuebec	-1.250	0.598	-2.089	0.037

```
glm(C ~ R, family = binomial, data = wlfdata)
```

w	df	p
2.4134751	1.0000000	0.1202951

LRT of CI
C ⊥ H | R



```
glm(H ~ R, family = binomial, data = wlfdata)
```

	Estimate	Std. Error	z value	Pr(> z)
(Intercept)	0.000	0.365	0.000	1.000
RBC	0.069	0.521	0.132	0.895
ROntario	0.298	0.414	0.721	0.471
RPrarie	-0.894	0.538	-1.660	0.097
RQuebec	-0.279	0.443	-0.629	0.529

```
glm(H ~ 1, family = binomial, data = wlfdata)
```

w	df	p
9.19254035	4.0000000	0.05646299

$H \not\perp R$