Decomposition of log-linear models

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A density f *factorizes* w.r.t. $\mathcal{A}$ if there exist functions $\psi_a(x)$ which depend on x_a only so that

$$f(x) = \prod_{a \in \mathcal{A}} \psi_a(x).$$

The set of distributions $\mathcal{P}_{\mathcal{A}}$ which factorize w.r.t. $\mathcal{A}$ is the *hierarchical log–linear model* generated by $\mathcal{A}$.

$\mathcal{A}$ is the *generating class* of the log–linear model.

For any generating class $\mathcal{A}$ we construct the dependence graph $G(\mathcal{A}) = G(\mathcal{P}_\mathcal{A})$ of the log–linear model $\mathcal{P}_\mathcal{A}$.

The dependence graph is determined by the relation

$$\alpha \sim \beta \iff \exists a \in \mathcal{A} : \alpha, \beta \in a.$$

For sets in $\mathcal{A}$ are clearly complete in $G(\mathcal{A})$ and therefore *distributions in $\mathcal{P}_\mathcal{A}$ do factorize according to $G(\mathcal{A})$*.

They are thus also global, local, and pairwise Markov w.r.t. $G(\mathcal{A})$.

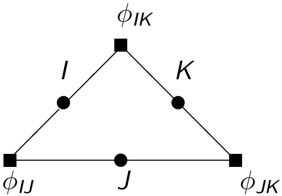
As a generating class defines a dependence graph $G(\mathcal{A})$, the reverse is also true.

The set $\mathcal{C}(\mathcal{G})$ of *cliques* (maximal complete subsets) of $\mathcal{G}$ is a generating class for the log–linear model of distributions which factorize w.r.t. $\mathcal{G}$.

If the dependence graph completely summarizes the restrictions imposed by $\mathcal{A}$, i.e. if

$$\mathcal{A} = \mathcal{C}(G(\mathcal{A})),$$

$\mathcal{A}$ is *conformal*.



The *factor graph* of $\mathcal{A}$ is the bipartite graph with vertices $V \cup \mathcal{A}$ and edges define by

$$\alpha \sim a \iff \alpha \in a.$$

Using this graph even non-conformal log–linear models admit a simple visual representation.

The maximum likelihood estimate $\hat{p}$ of p is the unique element of $\overline{\mathcal{P}_{\mathcal{A}}}$ which satisfies the system of equations

$$n\hat{p}(x_a) = n(x_a), \forall a \in \mathcal{A}, x_a \in \mathcal{X}_a. \tag{1}$$

Here $g(x_a) = \sum_{y:y_a=x_a} g(y)$ is the *a-marginal* of the function g. The system of equations (1) expresses the *fitting of the marginals* in $\mathcal{A}$.

There is a *convergent* algorithm which solves the likelihood equations. This cycles (repeatedly) through all the a-marginals in $\mathcal{A}$ and fit them one by one.

For $a \in \mathcal{A}$ define the following *scaling* operation on p:

$$(T_a p)(x) \leftarrow p(x) \frac{n(x_a)}{np(x_a)}, \quad x \in \mathcal{X}$$

where $0/0 = 0$ and $b/0$ is undefined if $b \neq 0$.

Make an ordering of the generators $\mathcal{A} = \{a_1, \ldots, a_k\}$. Define S by a full cycle of scalings

$$Sp = T_{a_k} \cdots T_{a_2} T_{a_1}.$$

Define the iteration

$$p_0(x) \leftarrow 1/|\mathcal{X}|, \quad p_n = Sp_{n-1}, n = 1, \ldots.$$

It then holds that

$$\lim_{n \to \infty} p_n = \hat{p}$$

where $\hat{p}$ is the unique maximum likelihood estimate of $p \in \overline{\mathcal{P}_{\mathcal{A}}}$, i.e. the solution of the equation system (1).

In some cases the IPS algorithm converges after a finite number of cycles. An explicit formula is then available for the MLE of $p \in \mathcal{P}_{\mathcal{A}}$.

Consider first the case of a generating class with only two elements: $\mathcal{A} = \{a, b\}$ and thus $V = a \cup b$. Let $c = a \cap b$. Recall that the MLE is the unique solution to

$$n\hat{p}(x_a) = n(x_a), \forall a \in \mathcal{A}, x_a \in \mathcal{X}_a.$$

Let

$$p^*(x) = \frac{n(x_a)n(x_b)}{n(x_c)n}.$$

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This satisfies (1) since e.g.

$$\begin{aligned} np^*(x_a) &= \sum_{y:y_a=x_a} \frac{n(y_a)n(y_b)}{n(y_c)} = \sum_{y:y_a=x_a} \frac{n(x_a)n(y_b)}{n(x_c)} \\ &= \frac{n(x_a)}{n(x_c)} \sum_{y:y_a=x_a} n(y_b) = \frac{n(x_a)}{n(x_c)} n(x_c) = n(x_a) \end{aligned}$$

and similarly with the other marginal. Hence we have $\hat{p} = p^*$.

The generating class $\mathcal{A} = \{a, b\}$ is conformal. Its dependence graph $\mathcal{G}$ has exactly two cliques a and b.

The graph is *chordal*, meaning that any cycle of length ≥ 4 has a chord.

$\mathcal{A}$ is called *decomposable* if $\mathcal{A}$ is conformal, i.e. $\mathcal{A} = \mathcal{C}(\mathcal{G})$, and $\mathcal{G}$ is chordal.

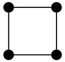
The IPS-algorithm converges after a finite number of cycles (at most two) if and only if $\mathcal{A}$ is decomposable.

Non-decomposable generating classes

A generating class can be non-decomposable in different ways.

The generating class $\mathcal{A} = \{\{1,2\},\{2,3\},\{1,3\}\}$ is the smallest non-decomposable generating class. This is non-conformal.

The graph below is the smallest non-chordal graph and its generating class is non-decomposable:

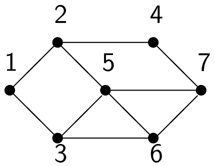


Consider an *undirected* graph $\mathcal{G} = (V, E)$. A partitioning of V into a triple (A, B, S) of subsets of V forms a *decomposition* of $\mathcal{G}$ if

$$A \perp_{\mathcal{G}} B \mid S \text{ and } S \text{ is complete.}$$

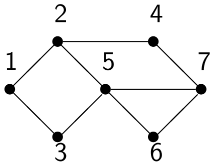
The decomposition is *proper* if $A \neq \emptyset$ and $B \neq \emptyset$.
The *components* of $\mathcal{G}$ are the induced subgraphs $\mathcal{G}_{A \cup S}$ and $\mathcal{G}_{B \cup S}$.
A graph is *prime* if no proper decomposition exists.

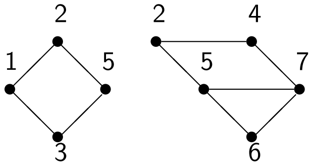
Examples



The graph to the left is prime

Decomposition with $A = \{1, 3\}$, $B = \{4, 6, 7\}$ and $S = \{2, 5\}$





Suppose P satisfies (F) w.r.t. $\mathcal{G}$ and (A, B, S) is a decomposition. Then

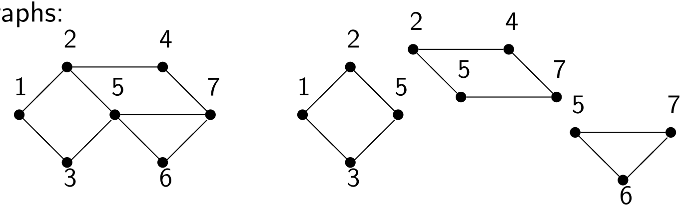
(i) *$P_{A\cup S}$ and $P_{B\cup S}$ satisfy (F) w.r.t. $\mathcal{G}_{A\cup S}$ and $\mathcal{G}_{B\cup S}$ respectively;*

(ii) $f(x)f_S(x_S) = f_{A\cup S}(x_{A\cup S})f_{B\cup S}(x_{B\cup S})$.

The converse also holds in the sense that *if (i) and (ii) hold, and (A, B, S) is a decomposition of $\mathcal{G}$, then P factorizes w.r.t. $\mathcal{G}$.*

Decomposability

Any graph can be recursively decomposed into its maximal prime subgraphs:



A graph is *decomposable* (or rather fully decomposable) if it is complete or admits a proper decomposition into *decomposable* subgraphs.

Definition is recursive. Alternatively this means that *all maximal prime subgraphs are cliques.*

Recursive decomposition of a decomposable graph into cliques yields the formula:

$$f(x)\prod_{S\in\mathcal{S}} f_S(x_S)^{\nu(S)} = \prod_{C\in\mathcal{C}} f_C(x_C).$$

Here $\mathcal{S}$ is the set of *minimal complete separators* occurring in the decomposition process and $\nu(S)$ the number of times such a separator appears in this process.

As we have a particularly simple factorization of the density, we have a similar factorization of the maximum likelihood estimate for a decomposable log-linear model.

The MLE for p under the log-linear model with generating class $\mathcal{A} = \mathcal{C}(\mathcal{G})$ *for a chordal graph* $\mathcal{G}$ *is*

$$\hat{p}(x) = \frac{\prod_{C \in \mathcal{C}} n(x_C)}{n \prod_{S \in \mathcal{S}} n(x_S)^{\nu(S)}}$$

where $\nu(S)$ *is the number of times* S *appears as a separator in the total decomposition of its dependence graph.*

Perfect numbering

A numbering $V = \{1, \ldots, |V|\}$ of the vertices of an undirected graph is *perfect* if

$$\forall j = 2, \ldots, |V| : \mathrm{bd}(j) \cap \{1, \ldots, j-1\} \text{ is complete in } \mathcal{G}.$$

A set S is an *(α, β)-separator* if $\alpha \perp_{\mathcal{G}} \beta \mid S$,

Characterizing chordal graphs

The following are equivalent for any undirected graph $\mathcal{G}$.

(i) *$\mathcal{G}$ is chordal;*

(ii) *$\mathcal{G}$ is decomposable;*

(iii) *All maximal prime subgraphs of $\mathcal{G}$ are cliques;*

(iv) *$\mathcal{G}$ admits a perfect numbering;*

(v) *Every minimal (α, β)-separator are complete.*

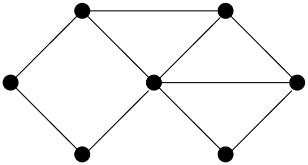
Trees are chordal graphs and thus decomposable.

Here is a (greedy) algorithm for checking chordality:

1. Look for a vertex v^* with $\mathrm{bd}(v^*)$ complete. *If no such vertex exists, the graph is not chordal.*
2. Form the subgraph $\mathcal{G}_{V \setminus v^*}$ and let $v^* = |V|$;
3. Repeat the process under 1;
4. *If the algorithm continues until only one vertex is left, the graph is chordal and the numbering is perfect.*

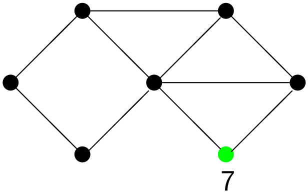
The complexity of this algorithm is $O(|V|^2)$.

Greedy algorithm



Is this graph chordal?

Greedy algorithm



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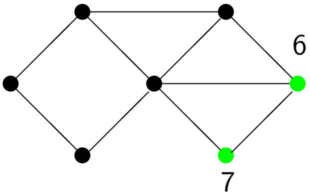

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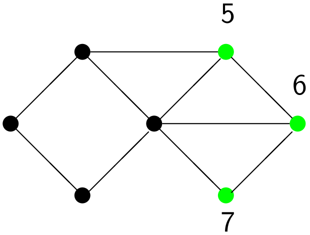

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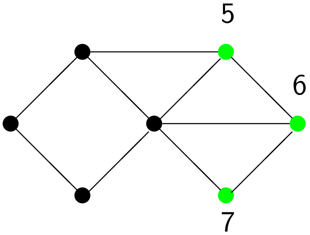
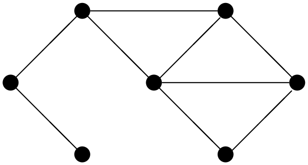


This graph is *not* chordal, as there is no candidate for number 4.

Greedy algorithm



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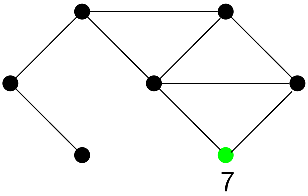

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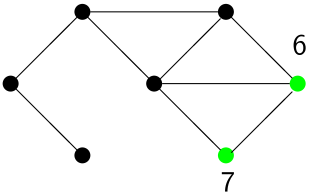

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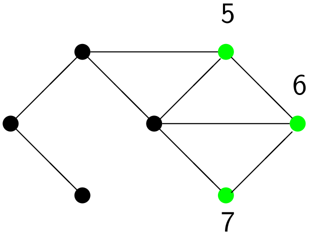

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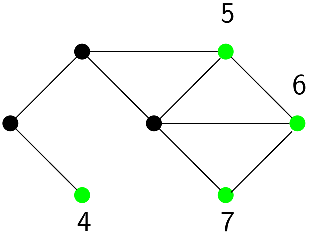

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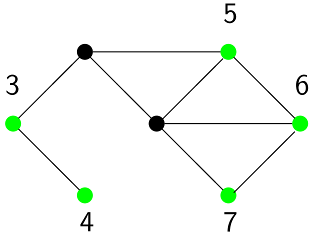

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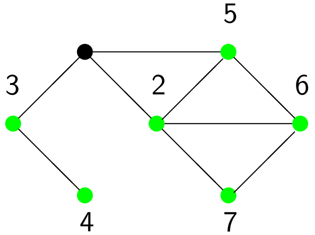

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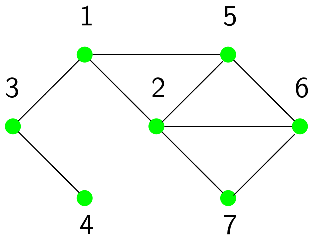
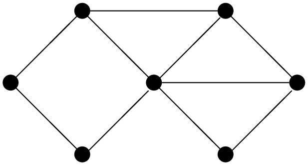


This graph is chordal!

This simple algorithm has complexity $O(|V| + |E|)$:

1. Choose $v_0 \in V$ arbitrary and let $v_0 = 1$;
2. When vertices $\{1, 2, \ldots, j\}$ have been identified, choose $v = j + 1$ among $V \setminus \{1, 2, \ldots, j\}$ with highest cardinality of its numbered neighbours;
3. *If* $\mathrm{bd}(j + 1) \cap \{1, 2, \ldots, j\}$ *is not complete,* $\mathcal{G}$ is not chordal;
4. Repeat from 2;
5. *If the algorithm continues until only one vertex is left, the graph is chordal and the numbering is perfect.*

Maximum Cardinality Search



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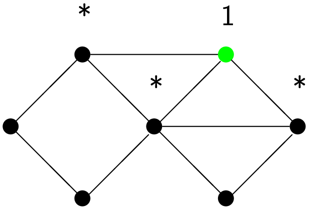
Maximum Cardinality Search



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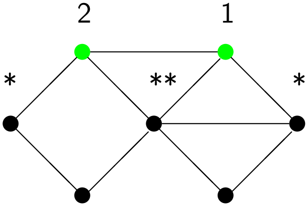

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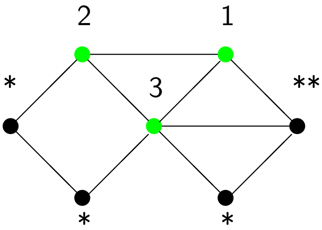

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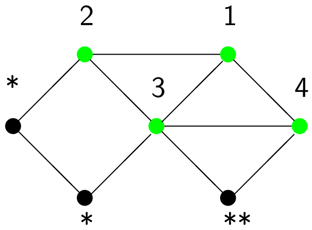

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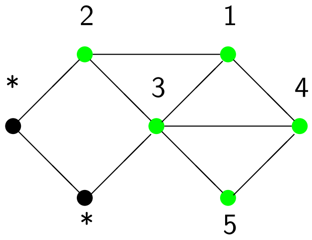

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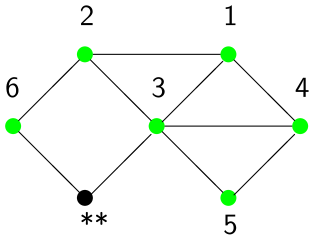

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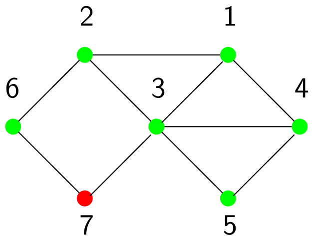
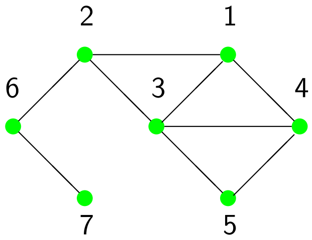


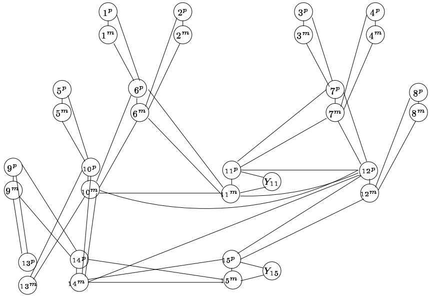
The graph is not chordal! because 7 does not have a complete boundary.

Maximum Cardinality Search



MCS numbering for the chordal graph. Algorithm runs essentially as before.

A chordal graph



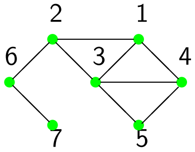
This graph is chordal, but it might not be that easy to see. . . Maximum Cardinality Search is handy!

Finding the cliques of a chordal graph

From an MCS numbering $V = \{1, \ldots, |V|\}$, let

$$B_\lambda = \mathrm{bd}(\lambda) \cap \{1, \ldots, \lambda - 1\}$$

and $\pi_\lambda = |B_\lambda|$. Call λ a *ladder vertex* if $\lambda = |V|$ or if $\pi_{\lambda+1} < \pi_\lambda + 1$. Let Λ be the set of ladder vertices.



π_λ: 0,1,2,2,2,1,1.

The cliques are $C_\lambda = \{\lambda\} \cup B_\lambda, \lambda \in \Lambda$.