Decision theoretic troubleshooting

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Light Print Problem

Your **trouble**:	"The page that came out of your printer is light."
Our **trouble-shooter**:	"Perform these steps that will help you solve the trouble."

Problem description:

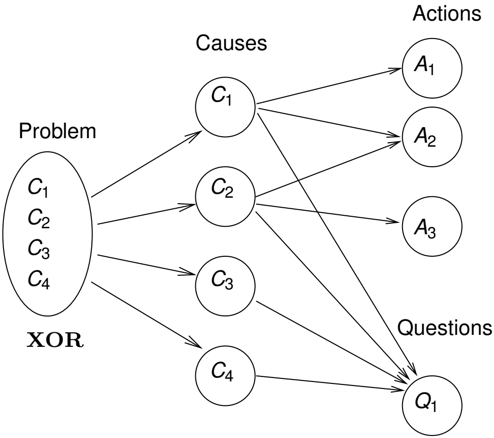
- *problem causes* $C \in \mathcal{C}$
- *actions* $A \in \mathcal{A}$ - troubleshooting steps that may solve the problem
- *questions* $Q \in \mathcal{Q}$ - troubleshooting steps that help identify the problem cause.
- every action and question has assigned a cost:
    - c_A ... cost of an action A
    - c_Q ... cost of a question Q

Light Print Problem - causes, actions and questions

Causes of light print	$p(C_i)$
C_1: `Distribution problem`	0.4
C_2: `Defective toner`	0.3
C_3: `Corrupted dataflow`	0.2
C_4: `Wrong driver setting`	0.1

Actions and questions	c_i
A_1: `Remove, shake and reseat toner`	5
A_2: `Try another toner`	15
A_3: `Cycle power`	1
Q_1: `Is the printer configuration page printed light?`	2

Light Print Problem - Bayesian Network



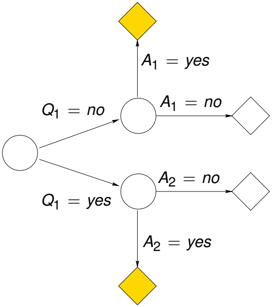
Light Print - conditional probability tables (CPT)

- for every action A_i and for every parent cause C_j an expert provides a CPT for $p(A_i = yes|C_j)$
- for every answer q_k to every question Q_k and for every parent cause C_j the expert provides a CPT for $p(Q_k = q_k|C_j)$

C_j	$p(A_2 = yes\|C_j)$
C_1	0.9
C_2	0.9
C_3	-
C_4	-

C_j	$p(Q_1 = yes\|C_j)$
C_1	1
C_2	1
C_3	0
C_4	0

Troubleshooting strategy



Expected Cost of Repair (ECR)

A strategy may terminate:

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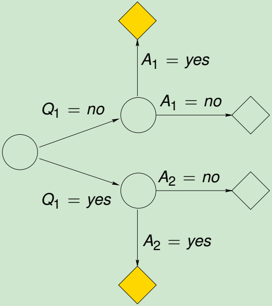
  - a penalty function $c(\mathbf{e}_\ell)$ applies
  - can be interpreted as a cost of calling service
- by solving the problem: $c(\mathbf{e}_\ell) \stackrel{\mathrm{def}}{=} 0$

Expected Cost of Repair (ECR)

Example



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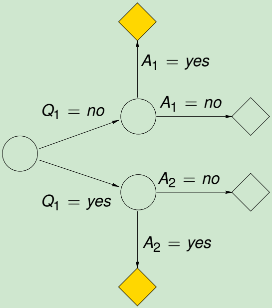

Strategy	Expected Cost of Repair (ECR)
$Q_1 \begin{cases} A_1 \\ A_2 \end{cases}$	$p(Q_1 = no, A_1 = yes) \cdot (c_{Q_1} + c_{A_1} + 0)$

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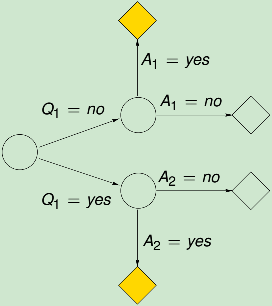

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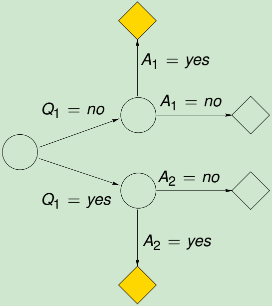

Strategy Expected Cost of Repair (ECR)

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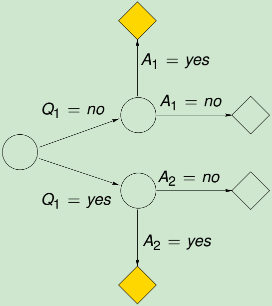

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\end{array}
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Expected Cost of Repair (ECR)

$$\text{Node } n \quad \mapsto \quad \mathbf{e}_n = \left\{ \begin{array}{l} (A = yes/no)_{A \,\in\, \{performed\ \ actions\}}\,, \\ (Q = yes/no)_{Q \,\in\, \{performed\ \ questions\}} \end{array} \right\}$$

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$$ECR(\mathbf{s}) = \sum_{\ell \in \{terminal\ nodes\ of\ \mathbf{s}\}} p(\mathbf{e}_\ell) \cdot [\ t(\mathbf{e}_\ell) + c(\mathbf{e}_\ell)\ ]$$

Optimal strategy

Optimal strategy $\mathbf{s}^\star$

$$\Longleftrightarrow$$

$$\mathbf{s}^\star \quad = \quad \arg\min_{\mathbf{s} \in \{all\ \ possible\ \ strategies\}} ECR(\mathbf{s})$$

Troubleshooting with dependent actions is NP-hard

Theorem (1)

Assume decision-theoretic troubleshooting problem with fixed costs and dependent actions. The decision whether there exists a troubleshooting sequence with $ECR \leq K$ *for a given constant* K *is NP-complete problem for both single fault assumption and independent faults.*

Proof:

- The problem is NP: if we guess a good sequence we calculate ECR and compare whether $ECR \leq K$. It takes polynomial time to calculate ECR of a sequence.

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- The problem is NP: if we guess a good sequence we calculate ECR and compare whether $ECR \leq K$. It takes polynomial time to calculate ECR of a sequence.
- The problem is NP-hard: We reduce the Exact cover by 3-sets to troubleshooting.

Exact cover by 3-sets

Definition (Exact cover by 3-sets)

We are given a family $F = \{S_1, \dots, S_n\}$ of subsets of a set U, such that $|U| = 3m$ for some integer m, and $|S_i| = 3$ for all i. We are asked if there are m sets in F that are disjoint and have U as their union.

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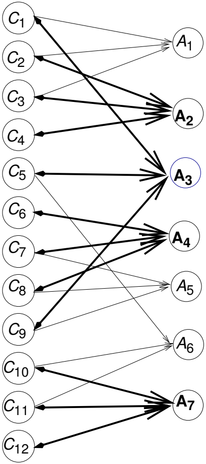
The proof of NP-completeness is for example in:
Christos H. Papadimitriou. *Computational complexity*. Addison-Wesley Publishing Company, 1994.

$p(C_i)$ uniform
$p(A_j|C_i) \in \{0,1\}$
$c_A = 1$
$c(\mathbf{e}_\ell) = 2 \cdot (m+1)^2$



$\mathbf{U} = \{\mathbf{1},\mathbf{2},\mathbf{3}\cdots,\mathbf{12}\}$

$S_1 = \{1,2,3\}$

$\mathbf{S_2} = \{\mathbf{2},\mathbf{3},\mathbf{4}\}$

$\mathbf{S_3} = \{\mathbf{1},\mathbf{5},\mathbf{9}\}$

$\mathbf{S_4} = \{\mathbf{6},\mathbf{7},\mathbf{8}\}$

$S_5 = \{7,8,9\}$

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COVER BY 3-SETS $\preceq$ Troubleshooting

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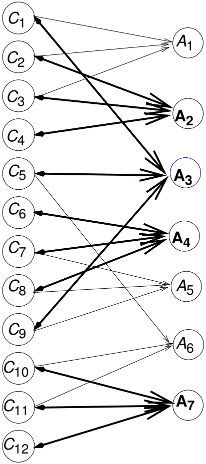

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The exact cover by 3-sets exists iff $ECR \leq \frac{m+1}{2}$ for some sequence.

Proof of NP-hardness - 1

Lemma (1)

If we have exact 3-sets cover $V = \{S_{j_1}, \ldots, S_{j_l}\}$ *then the ECR of corresponding action sequence* $A_{j_1}, \ldots, A_{j_l}$ *(in any order) has the* $ECR = \frac{m+1}{2}$.

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- In any step i we address three causes, therefore the value added in the terminal node i is $p(\mathbf{e}_i) \cdot t(\mathbf{e}_i) = [3 \cdot p(C)] \cdot i = 3 \cdot \frac{1}{3m} \cdot i = \frac{i}{m}$.

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Therefore: $$ECR(A_{j_1}, \ldots, A_{j_l}) = \sum_{i=1}^{m} \frac{i}{m} = \frac{(m+1) \cdot m}{2 \cdot m} = \frac{m+1}{2}.$$

Proof of NP-hardness - 2

Lemma (2)

$ECR(\boldsymbol{s}) \geq \frac{m+1}{2}$ for any sequence $\boldsymbol{s}$. If two actions in the sequence address the same cause then $ECR(\boldsymbol{s}) > \frac{m+1}{2}$.

Other troubleshooting models

$$T \left(\begin{array}{c} p(A|C) \in \{0,1\},\, p(C) = \frac{1}{|C|} \\ \textit{dependent actions} \\ ECR < K \end{array} \right) \textit{ is NP-complete}.$$

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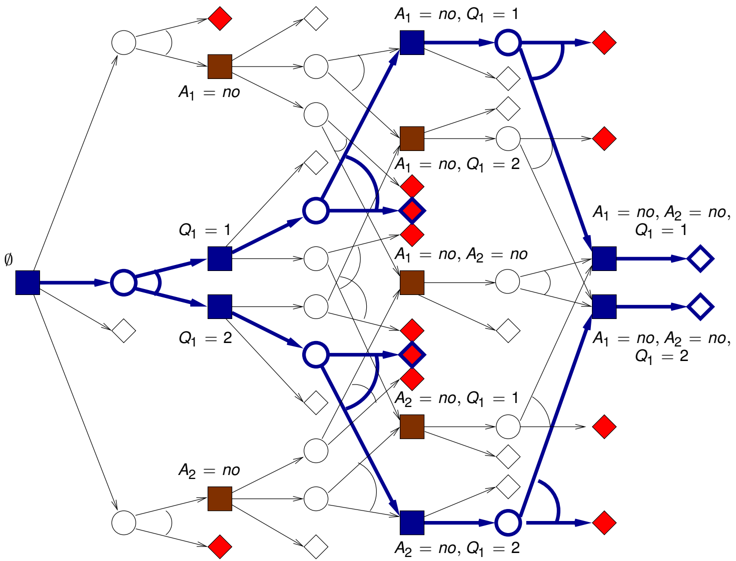
Search for an optimal strategy - 1



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$$
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- If we store $\mathbf{s}^\star(\mathbf{e}_n)$ for explored subtrees the we get a reduction in search complexity:

$$\mathcal{O}((n+m)!) \longrightarrow \mathcal{O}(2^{n+m})$$

Heuristic search for an optimal strategy

The goal:
$\widehat{ECR}(\mathbf{e}_n)$ ... an estimate of Expected Cost of Repair of strategy $\mathbf{s}^\star(\mathbf{e}_n)$ such that

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so that it is an **optimistic** heuristic.

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- Define

$$\widehat{ECR}(\mathbf{e}_n) \;=\; \sum_{C_i \in \mathcal{C}} p(C_i = yes \mid \mathbf{e}_n) \cdot ECR(\mathbf{s}_{\mathbf{e}_n}^{C_i} \mid \mathbf{e}_n \cup C_i = yes)$$

Computation of $\widehat{ECR}$

- For every cause C_i the actions that may solve the problem (i.e. such that $P(A = yes \mid C_i = yes) > 0$) are ordered according to

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Observe: an update of the model is necessary only for $p(C_i|\mathbf{e}_n)$.
No other expensive computations are required!

Branch&Bound

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- Store the temporary best $ECR'(\mathbf{e}_n)$
- If

$$C_S + \sum_{outcomes} P(S = outcome | e) \cdot \widehat{ECR}(e \cup S = outcome) \geq ECR'(\mathbf{e}_n)$$

then prune the branch starting with step S.

Branch&Bound

The algorithm performs a depth first search with pruning:

- Store the temporary best $ECR'(\mathbf{e}_n)$
- If

$$C_S + \sum_{outcomes} P(S = outcome|e) \cdot \widehat{ECR}(e \cup S = outcome) \geq ECR'(\mathbf{e}_n)$$

  then prune the branch starting with step S.

Since the applied estimate $\widehat{ECR}$ is optimistic the optimum is guaranteed.

$AO^{\star}$ algorithm

$A^{\star}$ algorithm for AND/OR graphs
(J. Pearl, Heuristics: intelligent search strategies for computer problem solving, 1984.)

- All not expanded neighbors of frontier nodes are evaluated using the heuristic function $\widehat{ECR}$.

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- From all partial strategies the cheapest one is chosen.
- A frontier node of the cheapest strategy is expanded (different approaches).

The first fully expanded strategy is optimum.

A real-time suboptimal search

Dezide troubleshooter:

- Developed in the Laboratory for Normative Systems, within a joint project of Hewlett-Packard and Aalborg University.

A real-time suboptimal search

Dezide troubleshooter:

- Developed in the Laboratory for Normative Systems, within a joint project of Hewlett-Packard and Aalborg University.
- Exploits several heuristics based on the p/c ratio.

Dezide troubleshooter vs. optimum (based on ECR)

Problem	$\mid\mathcal{A}\mid$	$\mid\mathcal{Q}\mid$	OPTIM	Dezide	LBE	P/C
53	6	2	**433.238**	443.305	501.625	444.544
Tray	9	3	**129.214**	129.214	131.585	155.096
Overrun	11	3	**106.204**	112.456	117.377	116.801
Load	12	3	**38.3777**	38.4229	42.6062	43.0535
Pjam	13	4	**124.323**	124.365	299.415	300.855
Scatter	14	4	**115.410**	115.862	324.38	236.578
NotDupl	9	9	**70.6740**	73.5984	77.3768	121.098
Spots	16	5	**161.385**	162.246	863.362	286.749
MIO1	10	10	**250.452**	253.310	355.943	479.956

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Software:

- Dezide - Bayesian automated diagnostics, `http://www.dezide.com`