

# Decision Networks

[RN2] Sections 16.5, 16.6  
[RN3] Sections 16.5, 16.6

CS 486/686  
University of Waterloo  
Lecture 11: Feb 16, 2012

## Outline

- Decision Networks
  - Aka Influence diagrams
- Value of information

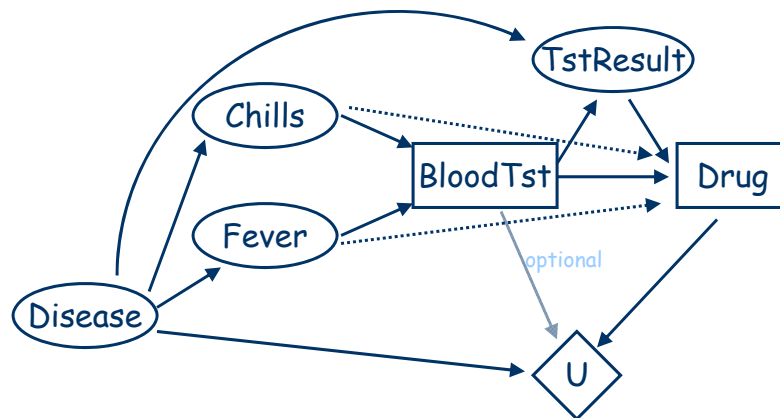
## Decision Networks

- *Decision networks* (also known as *influence diagrams*) provide a way of representing sequential decision problems
  - basic idea: represent the variables in the problem as you would in a BN
  - add decision variables - variables that you "control"
  - add utility variables - how good different states are

3

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Sample Decision Network



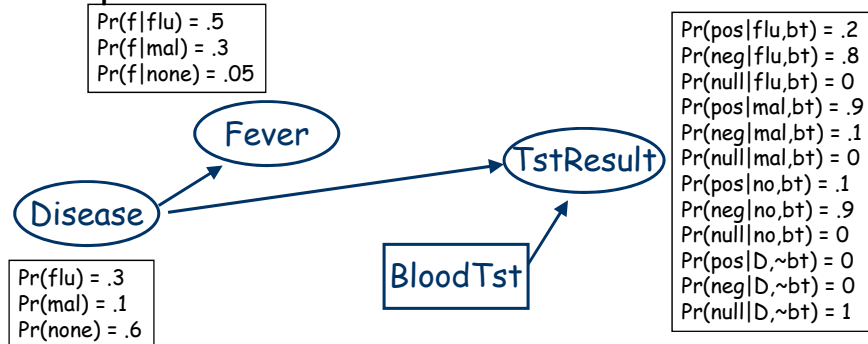
4

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Decision Networks: Chance Nodes

- **Chance nodes**

- random variables, denoted by circles
- as in a BN, probabilistic dependence on parents



CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

5

## Decision Networks: Decision Nodes

- **Decision nodes**

- variables set by decision maker, denoted by squares
- parents reflect *information available* at time decision is to be made
- Example: the actual values of Ch and Fev will be observed before the decision to take test must be made
  - agent can make *different decisions* for each instantiation of parents (i.e., policies)

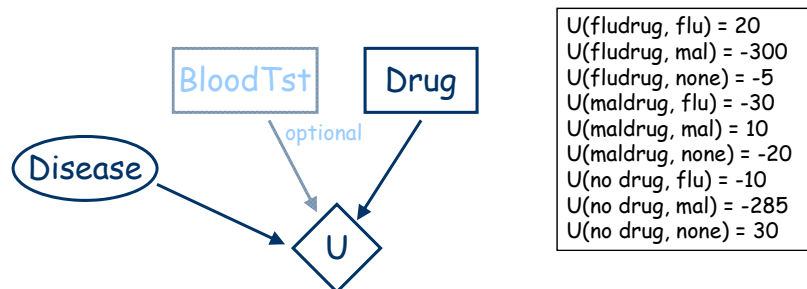


CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

6

## Decision Networks: Value Node

- **Value node**
  - specifies utility of a state, denoted by a diamond
  - utility depends *only on state of parents* of value node
  - generally: only one value node in a decision network
- Utility depends only on disease and drug

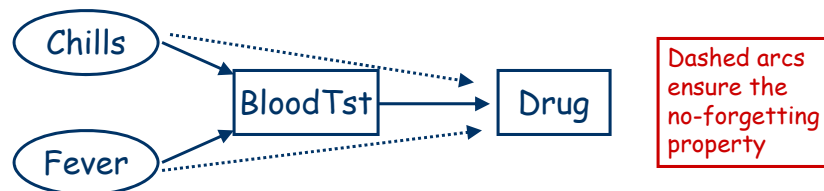


CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

7

## Decision Networks: Assumptions

- Decision nodes are totally ordered
  - decision variables  $D_1, D_2, \dots, D_n$
  - decisions are made in sequence
  - e.g., BloodTst (yes,no) decided before Drug (fd,md,no)
- *No-forgetting property*
  - any information available when decision  $D_i$  is made is available when decision  $D_j$  is made (for  $i < j$ )
  - thus all parents of  $D_i$  are parents of  $D_j$

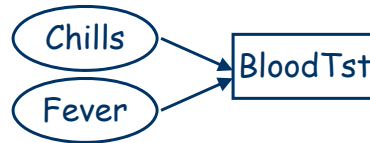


CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

8

## Policies

- Let  $Par(D_i)$  be the parents of decision node  $D_i$ 
  - $Dom(Par(D_i))$  is the set of assignments to parents
- A policy  $\delta$  is a set of mappings  $\delta_i$ , one for each decision node  $D_i$ 
  - $\delta_i : Dom(Par(D_i)) \rightarrow Dom(D_i)$
  - $\delta_i$  associates a decision with each parent asst for  $D_i$
- For example, a policy for BT might be:
  - $\delta_{BT}(c, f) = bt$
  - $\delta_{BT}(c, \sim f) = \sim bt$
  - $\delta_{BT}(\sim c, f) = bt$
  - $\delta_{BT}(\sim c, \sim f) = \sim bt$



9

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Value of a Policy

- *Value of a policy*  $\delta$  is the expected utility given that decision nodes are executed according to  $\delta$
- Given asst  $\mathbf{x}$  to the set  $\mathbf{X}$  of all chance variables, let  $\delta(\mathbf{x})$  denote the asst to decision variables dictated by  $\delta$ 
  - e.g., asst to  $D_1$  determined by it's parents' asst in  $\mathbf{x}$
  - e.g., asst to  $D_2$  determined by it's parents' asst in  $\mathbf{x}$  along with whatever was assigned to  $D_1$
  - etc.
- Value of  $\delta$ :

$$EU(\delta) = \sum_{\mathbf{x}} P(\mathbf{X}, \delta(\mathbf{X})) U(\mathbf{X}, \delta(\mathbf{X}))$$

10

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Optimal Policies

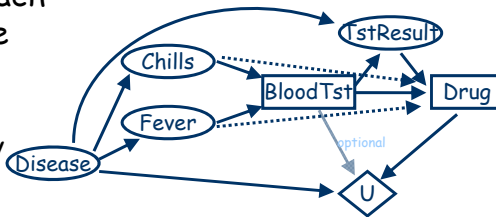
- An *optimal policy* is a policy  $\delta^*$  such that  $EU(\delta^*) \geq EU(\delta)$  for all policies  $\delta$
- We can use the dynamic programming principle yet again to avoid enumerating all policies
- We can also use the structure of the decision network to use **variable elimination** to aid in the computation

11

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Computing the Best Policy

- We can work backwards as follows
- First compute optimal policy for Drug (last dec'n)
  - for each asst to parents (C,F,BT,TR) and for each decision value (D = md,fd,none), *compute the expected value* of choosing that value of D
  - set policy choice for each value of parents to be the value of D that has max value
  - eg:  $\delta_D(c,f,bt,pos) = md$



12

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Computing the Best Policy

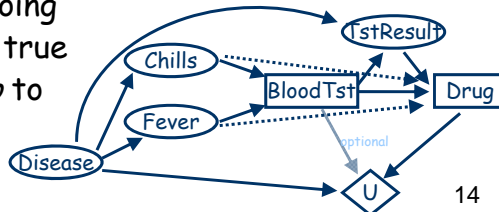
- Next compute policy for BT given policy  $\delta_D(C,F,BT,TR)$  just determined for Drug
  - since  $\delta_D(C,F,BT,TR)$  is fixed, we can treat Drug as a normal random variable with deterministic probabilities
  - i.e., for any instantiation of parents, value of Drug is fixed by policy  $\delta_D$
  - this means we can solve for optimal policy for BT just as before
  - only uninstantiated vars are random vars (once we fix *its* parents)

13

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Computing the Best Policy

- How do we compute these expected values?
  - suppose we have asst  $\langle c, f, bt, pos \rangle$  to parents of *Drug*
  - we want to compute EU of deciding to set *Drug* = *md*
  - we can run **variable elimination!**
- Treat *C, F, BT, TR, Dr* as evidence
  - this reduces factors (e.g., *U* restricted to *bt, md*: depends on *Dis*)
  - eliminate remaining variables (e.g., only *Disease* left)
  - left with factor:  **$EU(md|c, f, bt, pos) = \sum_{Dis} P(Dis|c, f, bt, pos, md) U(Dis, bt, md)$**
- We now know EU of doing *Dr=md* when *c, f, bt, pos* true
- Can do same for *fd, no* to decide which is best



14

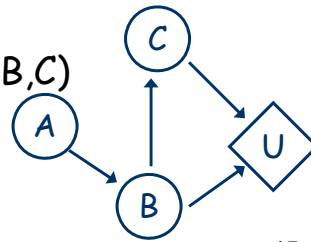
CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Computing Expected Utilities

- The preceding slide illustrates a general phenomenon
  - computing expected utilities with BNs is quite easy
  - utility nodes are just factors that can be dealt with using variable elimination

$$\begin{aligned} EU &= \sum_{A,B,C} P(A,B,C) U(B,C) \\ &= \sum_{A,B,C} P(C|B) P(B|A) P(A) U(B,C) \end{aligned}$$

- Just eliminate variables in the usual way



15

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Optimizing Policies: Key Points

- If a decision node D has no decisions that follow it, we can find its policy by instantiating each of its parents and computing the expected utility of each decision for each parent instantiation
  - no-forgetting means that all other decisions are instantiated (they must be parents)
  - its easy to compute the expected utility using VE
  - the number of computations is quite large: we run expected utility calculations (VE) for each parent instantiation together with each possible decision D might allow
  - policy: choose max decision for each parent instant'n

16

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson



## Optimizing Policies: Key Points

- When a decision D node is optimized, it can be treated as a random variable
  - for each instantiation of its parents we now know what value the decision should take
  - just treat policy as a new CPT: for a given parent instantiation  $\mathbf{x}$ , D gets  $\delta(\mathbf{x})$  with probability 1 (all other decisions get probability zero)
- If we optimize from last decision to first, at each point we can optimize a specific decision by (a bunch of) simple VE calculations
  - it's successor decisions (optimized) are just normal nodes in the BNs (with CPTs)

17

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Decision Network Notes

- Decision networks commonly used by decision analysts to help structure decision problems
- Much work put into computationally effective techniques to solve these
  - common trick: replace the decision nodes with random variables at outset and solve a plain Bayes net (a subtle but useful transformation)
- Complexity much greater than BN inference
  - we need to solve a number of BN inference problems
  - one BN problem for each setting of decision node parents and decision node value

18

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

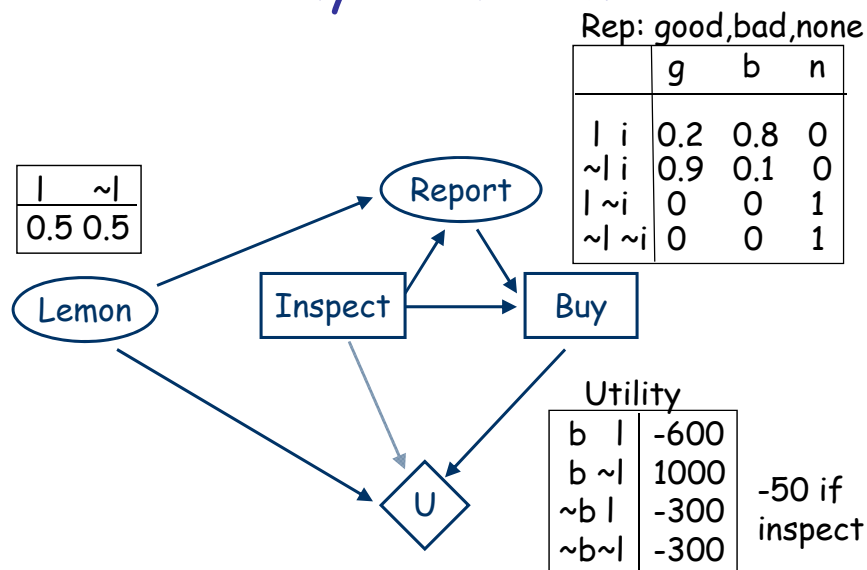
## A Decision Net Example

- Setting: you want to buy a used car, but there's a good chance it is a "lemon" (i.e., prone to breakdown). Before deciding to buy it, you can take it to a mechanic for inspection. S/he will give you a report on the car, labeling it either "good" or "bad". A good report is positively correlated with the car being sound, while a bad report is positively correlated with the car being a lemon.
- The report costs \$50 however. So you could risk it, and buy the car without the report.
- Owning a sound car is better than having no car, which is better than owning a lemon.

19

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Car Buyer's Network



20

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Evaluate Last Decision: Buy (1)

- $EU(B|I,R) = \sum_L P(L|I,R,B) U(L,I,B)$
- $I = i, R = g$ :
  - $EU(\text{buy}) = P(l|i,g,\text{buy}) U(l,i,\text{buy}) + P(\sim l|i,g,\text{buy}) U(\sim l,i,\text{buy})$   
 $= .18 \cdot -650 + .82 \cdot 950 = 662$
  - $EU(\sim\text{buy}) = P(l|i,g,\sim\text{buy}) U(l,i,\sim\text{buy}) + P(\sim l|i,g,\sim\text{buy}) U(\sim l,i,\sim\text{buy})$   
 $= -300 - 50 = -350$  (-300 indep. of lemon)
  - So optimal  $\delta_{Buy}(i,g) = \text{buy}$

21

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Evaluate Last Decision: Buy (2)

- $I = i, R = b$ :
  - $EU(\text{buy}) = P(l|i,b,\text{buy}) U(l,i,\text{buy}) + P(\sim l|i,b,\text{buy}) U(\sim l,i,\text{buy})$   
 $= .89 \cdot -650 + .11 \cdot 950 = -474$
  - $EU(\sim\text{buy}) = P(l|i,b,\sim\text{buy}) U(l,i,\sim\text{buy}) + P(\sim l|i,b,\sim\text{buy}) U(\sim l,i,\sim\text{buy})$   
 $= -300 - 50 = -350$  (-300 indep. of lemon)
  - So optimal  $\delta_{Buy}(i,b) = \sim\text{buy}$

22

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Evaluate Last Decision: Buy (3)

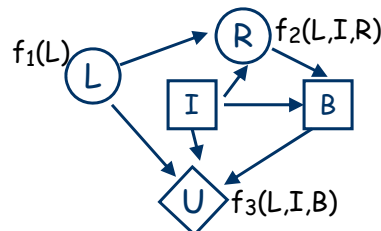
- $I = \sim i, R = n$ 
  - $EU(\text{buy}) = P(I|\sim i, n, \text{buy}) U(I, \sim i, \text{buy}) + P(\sim I|\sim i, n, \text{buy}) U(\sim I, \sim i, \text{buy})$   
 $= .5 \cdot -600 + .5 \cdot 1000 = 200$
  - $EU(\sim \text{buy}) = P(I|\sim i, n, \sim \text{buy}) U(I, \sim i, \sim \text{buy}) + P(\sim I|\sim i, n, \sim \text{buy}) U(\sim I, \sim i, \sim \text{buy})$   
 $= -300$  (-300 indep. of lemon)
  - So optimal  $\delta_{Buy}(\sim i, n) = \text{buy}$
- So optimal policy for Buy is:
  - $\delta_{Buy}(i, g) = \text{buy}; \delta_{Buy}(i, b) = \sim \text{buy}; \delta_{Buy}(\sim i, n) = \text{buy}$
- Note: we don't bother computing policy for  $(i, \sim n)$ ,  $(\sim i, g)$ , or  $(\sim i, b)$ , since these occur with probability 0

23

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Using Variable Elimination

**Factors:**  $f_1(L)$   $f_2(L, I, R)$   
 $f_3(L, I, B)$   
**Query:**  $EU(B)?$   
**Evidence:**  $I = i, R = g$   
**Elim. Order:**  $L$



Restriction: replace  $f_2(L, I, R)$  by  $f_4(L) = f_2(L, i, g)$   
 replace  $f_3(L, I, B)$  by  $f_5(L, B) = f_3(L, i, B)$

Step 1: Add  $f_6(B) = \sum_L f_1(L) f_4(L) f_5(L, B)$   
 Remove:  $f_1(L), f_4(L), f_5(L, B)$

Last factor:  $f_6(B)$  is proportional to the expected utility of buy and  $\sim$ buy. Select action with highest value.

Repeat for  $EU(B|i, b), EU(B|\sim i, n)$

24

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Alternatively

- N.B.: variable elimination for decision networks computes expected utility that are **not scaled**...
- Can still pick best action, since utility scale is not important (relative magnitude is what matters)
- If we want exact expected utility:
  - Let  $\mathbf{X} = \text{parents}(U)$
  - $EU(\text{dec}|\text{evidence}) = \sum_{\mathbf{X}} \Pr(\mathbf{X}|\text{dec}, \text{evidence}) U(\mathbf{X})$
  - Compute  $\Pr(\mathbf{X}|\text{dec}, \text{evidence})$  by variable elimination
  - Multiply  $\Pr(\mathbf{X}|\text{dec}, \text{evidence})$  by  $U(\mathbf{X})$
  - Summout  $\mathbf{X}$

25

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Evaluate First Decision: Inspect

- $EU(I) = \sum_{L,R} P(L,R|i) U(L,i, \delta_{Buy}(I,R))$ 
  - where  $P(R,L|i) = P(R|L,i)P(L|i)$
  - $EU(i) = (.1)(-650) + (.4)(-350) + (.45)(950) + (.05)(-350)$   
 $= 205$
  - $EU(\sim i) = P(n,l|\sim i) U(l,\sim i, \text{buy}) + P(n,\sim l|\sim i) U(\sim l,\sim i, \text{buy})$   
 $= .5 * -600 + .5 * 1000 = 200$
  - So optimal  $\delta_{Inspect}() = \text{inspect}$

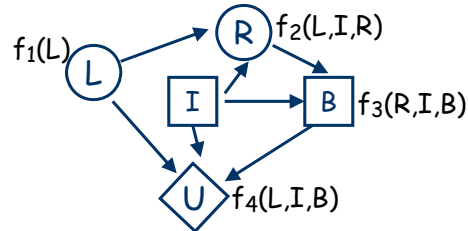
	$P(R,L   i)$	$\delta_{Buy}$	$U(L, i, \delta_{Buy})$
$g,l$	0.1	buy	$-600 - 50 = -650$
$b,l$	0.4	$\sim$ buy	$-300 - 50 = -350$
$g,\sim l$	0.45	buy	$1000 - 50 = 950$
$b,\sim l$	0.05	$\sim$ buy	$-300 - 50 = -350$

26

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Using Variable Elimination

**Factors:**  $f_1(L)$   $f_2(L,I,R)$   
 $f_3(R,I,B)$   $f_4(L,I,B)$   
**Query:**  $EU(I)?$   
**Evidence:** none  
**Elim. Order:** L, R, B



N.B.  $f_3(R,I,B) = \delta_B(R,I)$

Step 1: Add  $f_5(R,I,B) = \sum_L f_1(L) f_2(L,I,R) f_4(L,I,B)$   
 Remove:  $f_1(L) f_2(L,I,R) f_4(L,I,B)$

Step 2: Add  $f_6(I,B) = \sum_R f_3(R,I,B) f_5(R,I,B)$   
 Remove:  $f_3(R,I,B) f_5(R,I,B)$

Step 3: Add  $f_7(I) = \sum_B f_6(I,B)$   
 Remove:  $f_6(I,B)$

Last factor:  $f_7(I)$  is the expected utility of inspect and ~inspect.  
 Select action with highest expected utility.

27

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Value of Information

- So optimal policy is: inspect the car and if the report is good buy, otherwise don't buy
  - $EU = 205$
  - Notice that the EU of inspecting the car, then buying it iff you get a good report is 205 (i.e.,  $255 - 50$  (cost of inspection)) which is greater than 200. So inspection improves EU.
  - Suppose inspection cost is \$60: would it be worth it?
    - $EU = 255 - 60 = 195 < EU(\sim i)$
  - The *expected value of information* associated with inspection is 55 (it improves expected utility by this amount ignoring cost of inspection). How? Gives opportunity to change decision ( $\sim$ buy if bad).
  - You should be willing to pay up to \$55 for the report

28

CS486/686 Lecture Slides (c) 2012 C. Boutilier, P. Poupart & K. Larson

## Next Class

- Probabilistic reasoning over time
  - Dynamic Bayesian networks
  - Markov models