Informatics 2D – Reasoning and Agents

Semester 2, 2019–2020

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Lecture 29 – Decision Making Under Uncertainty

26th March 2020

Where are we?

Last time . . .

- Looked at Dynamic Bayesian Networks
- General, powerful method for describing temporal probabilistic problems
- Unfortunately exact inference computationally too hard
- Methods for approximate inference (particle filtering)

Today . . .

- **Decision Making under Uncertainty**

Combining beliefs and desires

- Rational agents do things that are an optimal tradeoff between:
  - the likelihood of reaching a particular resultant state (given one's actions) and
  - The desirability of that state
- So far we have done the 'likelihood' bit: we know how to evaluate the probability of being in a particular state at a particular time.
- But we've not looked at an agent's preferences or desires
- Now we will discuss **utility theory** in more detail to obtain a full picture of decision-theoretic agent design

Utility theory & utility functions

- Agent's preferences between world states are described using a **utility function**
- UF assigns some numerical value $U(S)$ to each state S to express its desirability for the agent
- Nondeterministic action a has results $Result(a)$ and probabilities $P(Result(a) = s'|a, \mathbf{e})$ summarise agent's knowledge about its effects given evidence observations $\mathbf{e}$.
- Can be combined with probabilities for outcomes to obtain **expected utility** of action:

$$EU(A|E) = \sum_{s'} P(Result(a) = s'|a, \mathbf{e})U(s')$$

Utility theory & utility functions

- Principle of **maximum expected utility** (MEU) says agent should use action that maximises expected utility
- In a sense, this summarises the whole endeavour of AI:

  If agent maximises utility function that correctly reflects the performance measure applied to it, then optimal performance will be achieved by averaging over all environments in which agent could be placed

- Of course, this doesn't tell us how to define utility function or how to determine probabilities for any sequence of actions in a complex environment
- For now we will only look at **one-shot decisions**, not **sequential decisions** (next lecture)

Constraints on rational preferences

- MEU sounds reasonable, but why should this be the best quantity to maximise? Why are numerical utilities sensible? Why single number?
- Questions can be answered by looking at constraints on preferences
- Notation:

$A \succ B$	A is preferred to B
$A \sim B$	the agent is indifferent between A and B
$A \succsim B$	the agent prefers A to B or is indifferent between them

- But what are A and B? Introduce **lotteries** with outcomes $C_1 \dots C_n$ and accompanying probabilities $L = [p_1, C_1; p_2, C_2; \dots; p_n, C_n]$

Constraints on rational preferences

- Outcome of a lottery can be state or another lottery
- Can be used to understand how preferences between complex lotteries are defined in terms of preferences among their (outcome) states
- The following are considered reasonable **axioms of utility theory**
- **Orderability**: $(A \succ B) \vee (B \succ A) \vee (A \sim B)$
- **Transitivity**: If agent prefers A over B and B over C then he must prefer A over C: $(A \succ B) \wedge (B \succ C) \Rightarrow (A \succ C)$
- Example: Assume $A \succ B \succ C \succ A$ and A, B, C are goods
  - Agent might trade A and some money for C if he has A
  - We then offer B for C and some cash and then trade A for B
  - Agent would lose all his money over time

Constraints on rational preferences

- **Continuity**: If B is between A and C in preference, then with some probability agent will be indifferent between getting B for sure and a lottery over A and C

$$A \succ B \succ C \Rightarrow \exists p\, [p, A; 1-p, C] \sim B$$

- **Substitutability**: Indifference between lotteries leads to indifference between complex lotteries built from them

$$A \sim B \Rightarrow [p, A; 1-p, C] \sim [p, B; 1-p, C]$$

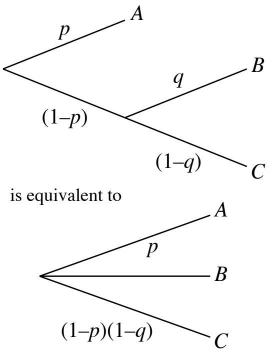
- **Monotonicity**: Preferring A to B implies preference for any lottery that assigns higher probability to A

$$A \succ B \Rightarrow (p \geq q \Leftrightarrow [p, A; 1-p, B] \succsim [q, A; 1-q, B]$$

Decomposability example

- **Decomposability**: Compound lotteries can be reduced to simpler one

$$[p, A; 1-p, [q, B; 1-q, C]] \sim [p, A; (1-p)q, B; (1-p)(1-q), C]$$



From preferences to utility

- The following **axioms of utility** ensure that utility functions follow the above axioms on preference:
  - Utility principle: there exists a function such that

$$U(A) > U(B) \Leftrightarrow A \succ B \quad U(A) = U(B) \Leftrightarrow A \sim B$$

  - MEU principle: utility of lottery is sum of probability of outcomes times their utilities

$$U([p_1, S_1; \ldots; p_n, S_n]) = \sum_i p_i U(S_i)$$

- But an agent might not know even his own utilities!
- But you can work out his (or even your own!) utilities by observing his (your) behaviour and assuming that he (you) chooses to MEU.

Utility functions

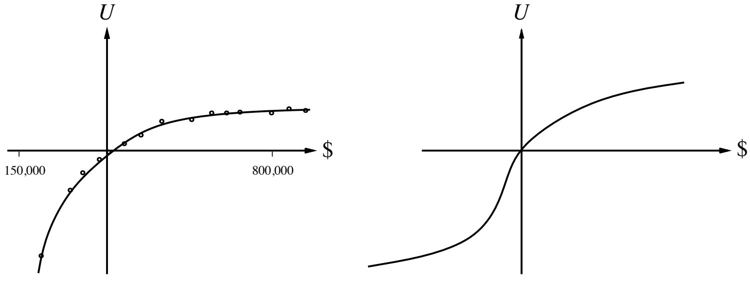
- According to the above axioms, arbitrary preferences can be expressed by utility functions
  - I prefer to have a prime number of £in my bank account; when I have £10 I will give away £3.
- But usually preferences are more systematic, a typical example being money (roughly, we like to maximise our money)
- Agents exhibit **monotonic preference** toward money, but how about lotteries involving money?
- "Who wants to be a millionaire"-type problem, is pocketing a smaller amount irrational?
- **Expected monetary value** (EMV) is actual expectation of outcome

Utility of money

- Assume you can keep 1 million or risk it with the prospect of getting three millions at the toss of a (fair) coin
- EMV of accepting gamble is $0.5 \times 0 + 0.5 \times 3,000,000$ which is greater than $1,000,000$
- Use S_n to denote state of possessing wealth "n dollars", current wealth S_k
- Expected utilities become:
  - $EU(Accept) = \frac{1}{2}U(S_k) + \frac{1}{2}U(S_{k+3,000,000})$
  - $EU(Decline) = U(S_{k+1,000,000})$
- But it all depends on utility values you assign to levels of monetary wealth (is first million more valuable than second?)

Utility of money (empirical study)

- It turns out that for most people this is usually concave (curve (a)), showing that going into debt is considered disastrous relative to small gains in money—**risk averse**.



(a) (b)

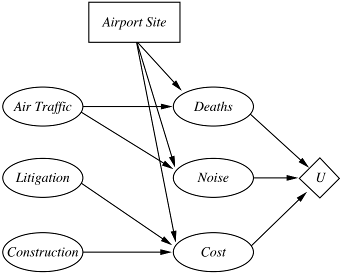
- But if you're already $10M in debt, your utility curve is more like (b)—**risk seeking** when desperate!

Utility scales

- Axioms don't say anything about scales
- For example transformation of $U(S)$ into $U'(S) = k_1 + k_2 U(S)$ (k_2 positive) doesn't affect behaviour
- In deterministic contexts behaviour is unchanged by any monotonic transformation (utility function is **value function/ordinal function**)
- One procedure for assessing utilities is to use **normalised utility** between "best possible prize" ($u^\top = 1$) and "worst possible catastrophe" ($u^\perp = 0$)
- Ask agent to indicate preference between S and the standard lottery $[p, u^\top : (1-p), u^\perp]$, adjust p until agent is indifferent between S and standard lottery, set $U(S) = p$

Decision networks

- What we now need is a way of integrating utilities into our view of probabilistic reasoning
- **Decision networks** (**influence diagrams**) combine BNs with additional node types for actions and utilities
- Illustrate with airport siting problem:

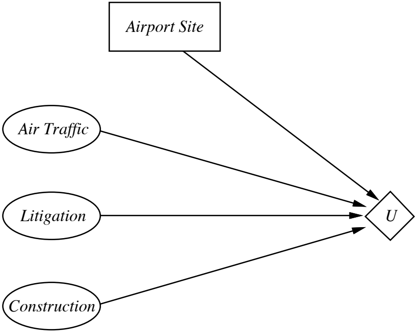


Representing decision problems with DNs

- **Chance nodes** (ovals) represent random variables with CPTs, parents can be decision nodes
- **Decision nodes** represent decision-making points at which actions are available
- **Utility nodes** represent utility function connected to all nodes that affect utility directly
- Often nodes describing outcome states are omitted and expected utility associated with actions is expressed (rather than states) – **action-utility tables**

Representing decision problems with DNs

- Simplified version with action-utility tables
- Less flexible but simpler (like pre-compiled version of general case)



Evaluating decision networks

- Evaluation of a DN works by setting decision node to every possible value
- "Algorithm":
  1. Set evidence variables for current state
  2. For each value of decision node:
     - 2.1 Set decision node to that value
     - 2.2 Calculate posterior probabilities for parents of utility node
     - 2.3 Calculate resulting (expected) utility for action
  3. Return action with highest (expected) utility
- Using any algorithm for BN inference, this yields a simple framework for building agents that make single-shot decisions

Summary

- Foundations for rational decision making under uncertainty
- Utility theory and its axioms, utility functions
- Possible points of criticism?
- Decision networks nicely blend with our BN framework
- Only looked at one-shot decisions so far
- Next time: **Markov Decision Processes**