Quantum Social Science

(A review of a recent book by E. Haven and A. Khrennikov)

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Outline
Decision Making: . . .
The Notion of Utility
Subjective Probabilities
Example of Seemingly . . .
Relation to Quantum . . .
From Individual to . . .
Alternative (Non- . . .
Why Humans Use . . .

1. Outline

- Decision theory – how to describe preferences if people behave rationally.
- In practice, people sometimes deviate from rational behavior.
- In some cases, quantum-type models are helpful in explaining actual human behavior.
- The authors use this to explain fluctuations of the stock market prices.
- They also speculate on why humans use quantum-stype reasoning.

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2. Decision Making: General Need and Traditional Approach

- To make a decision, we must:
  - find out the user's preference, and
  - help the user select an alternative which is the best – according to these preferences.
- Traditional approach is based on an assumption that for each two alternatives A' and A'', a user can tell:
  - whether the first alternative is better for him/her; we will denote this by $A'' < A'$;
  - or the second alternative is better; we will denote this by $A' < A''$;
  - or the two given alternatives are of equal value to the user; we will denote this by $A' = A''$.

3. The Notion of Utility

- Under the above assumption, we can form a natural numerical scale for describing preferences.
- Let us select a very bad alternative A_0 and a very good alternative A_1.
- Then, most other alternatives are better than A_0 but worse than A_1.
- For every prob. $p \in [0, 1]$, we can form a lottery $L(p)$ in which we get A_1 w/prob. p and A_0 w/prob. $1 - p$.
- When $p = 0$, this lottery simply coincides with the alternative A_0: $L(0) = A_0$.
- The larger the probability p of the positive outcome increases, the better the result:

$$p' < p'' \text{ implies } L(p') < L(p'').$$

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4. The Notion of Utility (cont-d)

- Finally, for $p = 1$, the lottery coincides with the alternative A_1: $L(1) = A_1$.
- Thus, we have a continuous scale of alternatives $L(p)$ that monotonically goes from $L(0) = A_0$ to $L(1) = A_1$.
- Due to monotonicity, when p increases, we first have $L(p) < A$, then we have $L(p) > A$.
- The threshold value is called the *utility* of the alternative A:

$$u(A) \stackrel{\text{def}}{=} \sup\{p : L(p) < A\} = \inf\{p : L(p) > A\}.$$

- Then, for every $\varepsilon > 0$, we have

$$L(u(A) - \varepsilon) < A < L(u(A) + \varepsilon).$$

- We will describe such (almost) equivalence by $\equiv$, i.e., we will write that $A \equiv L(u(A))$.

5. Fast Iterative Process for Determining $u(A)$

- *Initially:* we know the values $\underline{u} = 0$ and $\overline{u} = 1$ such that $A \equiv L(u(A))$ for some $u(A) \in [\underline{u}, \overline{u}]$.
- *What we do:* we compute the midpoint $u_{\rm mid}$ of the interval $[\underline{u}, \overline{u}]$ and compare A with $L(u_{\rm mid})$.
- *Possibilities:* $A \le L(u_{\rm mid})$ and $L(u_{\rm mid}) \le A$.
- *Case 1:* if $A \le L(u_{\rm mid})$, then $u(A) \le u_{\rm mid}$, so
$$u \in [\underline{u}, u_{\rm mid}].$$
- *Case 2:* if $L(u_{\rm mid}) \le A$, then $u_{\rm mid} \le u(A)$, so
$$u \in [u_{\rm mid}, \overline{u}].$$
- After each iteration, we decrease the width of the interval $[\underline{u}, \overline{u}]$ by half.
- After k iterations, we get an interval of width 2^{-k} which contains $u(A)$ – i.e., we get $u(A)$ w/accuracy 2^{-k}.

6. How to Make a Decision Based on Utility Values

- Suppose that we have found the utilities $u(A')$, $u(A'')$, ..., of the alternatives A', A'', ...
- Which of these alternatives should we choose?
- By definition of utility, we have:
  - $A \equiv L(u(A))$ for every alternative A, and
  - $L(p') < L(p'')$ if and only if $p' < p''$.
- We can thus conclude that A' is preferable to A'' if and only if $u(A') > u(A'')$.
- In other words, we should always select an alternative with the largest possible value of utility.

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7. How to Estimate Utility of an Action

- For each action, we usually know possible outcomes $S_1, \ldots, S_n$.
- We can often estimate the prob. $p_1, \ldots, p_n$ of these outcomes.
- By definition of utility, each situation S_i is equiv. to a lottery $L(u(S_i))$ in which we get:
  - A_1 with probability $u(S_i)$ and
  - A_0 with the remaining probability $1 - u(S_i)$.
- Thus, the action is equivalent to a complex lottery in which:
  - first, we select one of the situations S_i with probability p_i: $P(S_i) = p_i$;
  - then, depending on S_i, we get A_1 with probability $P(A_1 \mid S_i) = u(S_i)$ and A_0 w/probability $1 - u(S_i)$.

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8. How to Estimate Utility of an Action (cont-d)

- *Reminder:*
  - first, we select one of the situations S_i with probability p_i: $P(S_i) = p_i$;
  - then, depending on S_i, we get A_1 with probability $P(A_1 \mid S_i) = u(S_i)$ and A_0 w/probability $1 - u(S_i)$.
- The prob. of getting A_1 in this complex lottery is:

$$P(A_1) = \sum_{i=1}^{n} P(A_1 \mid S_i) \cdot P(S_i) = \sum_{i=1}^{n} u(S_i) \cdot p_i.$$

- In the complex lottery, we get:
  - A_1 with prob. $u = \sum\limits_{i=1}^{n} p_i \cdot u(S_i)$, and
  - A_0 w/prob. $1 - u$.
- So, we should select the action with the largest value of expected utility $u = \sum p_i \cdot u(S_i)$.

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9. Non-Uniqueness of Utility

- The above definition of utility u depends on A_0, A_1.
- What if we use different alternatives A'_0 and A'_1?
- Every A is equivalent to a lottery $L(u(A))$ in which we get A_1 w/prob. $u(A)$ and A_0 w/prob. $1 - u(A)$.
- For simplicity, let us assume that $A'_0 < A_0 < A_1 < A'_1$.
- Then, $A_0 \equiv L'(u'(A_0))$ and $A_1 \equiv L'(u'(A_1))$.
- So, A is equivalent to a complex lottery in which:
  1) we select A_1 w/prob. $u(A)$ and A_0 w/prob. $1-u(A)$;
  2) depending on A_i, we get A'_1 w/prob. $u'(A_i)$ and A'_0 w/prob. $1 - u'(A_i)$.
- In this complex lottery, we get A'_1 with probability $u'(A) = u(A) \cdot (u'(A_1) - u'(A_0)) + u'(A_0)$.
- So, in general, utility is defined modulo an (increasing) linear transformation $u' = a \cdot u + b$, with $a > 0$.

10. Subjective Probabilities

- In practice, we often do not know the probabilities p_i of different outcomes.
- For each event E, a natural way to estimate its subjective probability is to fix a prize (e.g., \$1) and compare:
  - the lottery ℓ_E in which we get the fixed prize if the event E occurs and 0 is it does not occur, with
  - a lottery $\ell(p)$ in which we get the same amount with probability p.
- Here, similarly to the utility case, we get a value $ps(E)$ for which, for every $\varepsilon > 0$:

$$\ell(ps(E) - \varepsilon) < \ell_E < \ell(ps(E) + \varepsilon).$$

- Then, the utility of an action with possible outcomes $S_1, \ldots, S_n$ is equal to $u = \sum_{i=1}^{n} ps(E_i) \cdot u(S_i)$.

11. Example of Seemingly Irrational Behavior

- *An urn* contains red (R), green (G), and blue (B) balls.
- *We know* that exactly 1/3 of balls are red: $p(R) = 1/3$.
- *We do not know* $p(G)$.
- *1st experiment:* choose between two alternatives:

  R: \$1 if a randomly chosen ball is red, \$0 otherwise;

  G: \$1 if a random ball is green, \$0 otherwise.
- *Result:* most people select alternative R: $G < R$.
- *In terms of utility:* we can take $u(\$0) = 0$, $u(\$1) = 1$.
- In this case, $u(R) = (1/3) \cdot u(\$1) + (2/3) \cdot u(\$0) = 1/3$ and $u(G) = ps(G) \cdot u(\$1) + (1 - ps(G)) \cdot u(\$0) = ps(G)$.
- Since $G < R$, this means that $ps(G) < 1/3$.

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12. Seemingly Irrational Behavior (cont-d)

- *Second experiment:* a person is asked to choose between two alternatives:

GB: you get \$1 if a randomly picked ball is either green or blue and \$0 otherwise;

RB: you get \$1 if a randomly picked ball is either red or blue and \$0 otherwise.

- *Result:* most people select alternative GB: $RB < GB$.
- *In terms of utility:*

$$u(GB) = (2/3) \cdot u(\$1) + (1/3) \cdot u(\$0) = 2/3;$$

$$u(RB) = (1 - ps(G)) \cdot u(\$1) + ps(G) \cdot u(\$0) = 1 - ps(G).$$

- Since $RB < GB$, this means that for most people, $1 - ps(G) < 2/3$ and thus, $ps(G) > 1/3$.
- *Contradiction:* this conclusion is inconsistent with the previous conclusion $ps(G) < 1/3$.

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13. Relation to Quantum Physics

- Here, $ps(G) < 1/3$, $ps(B) < 1/3$, but $ps(G \vee B) = 2/3$.
- In other words, here, $ps(G \vee B) \neq ps(G) + ps(B)$.
- Such situations are typical for *quantum processes*.
- *Example:* a photon source is separated from the sensors by a wall with two doors.
- If we open one door or both doors, some photons pass to the sensors.
- We can open the first door and count how many photos passed to the sensors.
- Let p_1 be the resulting probability.
- We can open the second door and count how many photos passed to the sensors.
- Let p_2 be the resulting probability.

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14. Relation to Quantum Physics (cont-d)

- If both doors are open, then a photon can pass:
  - either through the 1st door
  - or through the 2nd door
  - but not through both doors.
- So, we expect $p_{12} = p_1 + p_2$.
- In practice, $p_{12} \neq p_1 + p_2$.
- *Quantum description:* we have complex *amplitudes* Ψ_1 and Ψ_2 such that $p_1 = |\Psi_1|^2$ and $p_2 = |\Psi_2|^2$.
- Here, $p_{12} = |\Psi_{12}|^2$, where $\Psi_{12} = \Psi_1 + \Psi_2$.
- In general, $|\Psi_1 + \Psi_2|^2 \neq |\Psi_1|^2 + |\Psi|^2$, so $p_{12} \neq p_1 + p_2$.
- *Interesting:* kids going to candy boxes behave similarly to photons.

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15. From Individual to Collective Behavior

- Psychologists have performed many experiments showing such irrational behavior.
- Several models have been proposed explaining such behavior.
- These models, however, are far from perfect when describing individual decision making.
- At first glance, the problem of describing such irrational behavior,
  - while important in psychology,
  - is not of large practical interest.
- The authors notice, however, that:
  - a combination of such irrational behaviors
  - leads, e.g., to seemingly irrational fluctuations of the stock market.

16. Collective Behavior (cont-d)

- In contrast to highly irregular individual behavior, such group behavior is much more regular.
- It can be reasonably well described by known mathematical models.
- For example, we can use quantum-type stochastic differential equations.
- In the first approximation, the resulting equations are similar to Schroedinger's equations of quantum physics.
- A detailed analysis shows that the stock market dynamics is somewhat different from quantum dynamics.

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17. Alternative (Non-Quantum) Explanation

- Previously, we assumed that a user can always decide which of the two alternatives A' and A'' is better:
  - either $A' < A''$,
  - or $A'' < A'$,
  - or $A' \equiv A''$.
- In practice, a user is sometimes unable to meaningfully decide between the two alternatives; denoted $A' \parallel A''$.
- In mathematical terms, this means that the preference relation:
  - is no longer a *total* (linear) order,
  - it can be a *partial* order.

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18. From Utility to Interval-Valued Utility

- Similarly to the traditional decision making approach:
  - we select two alternatives $A_0 < A_1$ and
  - we compare each alternative A which is better than A_0 and worse than A_1 with lotteries $L(p)$.
- Since preference is a *partial* order, in general:

$$\underline{u}(A) \stackrel{\text{def}}{=} \sup\{p : L(p) < A\} < \overline{u}(A) \stackrel{\text{def}}{=} \inf\{p : L(p) > A\}.$$

- For each alternative A, instead of a single value $u(A)$ of the utility, we now have an *interval* $[\underline{u}(A), \overline{u}(A)]$ s.t.:
  - if $p < \underline{u}(A)$, then $L(p) < A$;
  - if $p > \overline{u}(A)$, then $A < L(p)$; and
  - if $\underline{u}(A) < p < \overline{u}(A)$, then $A \parallel L(p)$.
- We will call this interval the *utility* of the alternative A.

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19. Interval-Valued Utilities and Interval-Valued Subjective Probabilities

- To feasibly elicit the values $\underline{u}(A)$ and $\overline{u}(A)$, we:

  1) starting w/$[\underline{u}, \overline{u}] = [0, 1]$, bisect an interval s.t. $L(\underline{u}) < A < L(\overline{u})$ until we find u_0 s.t. $A \parallel L(u_0)$;
  2) by bisecting an interval $[\underline{u}, u_0]$ for which $L(\underline{u}) < A \parallel L(u_0)$, we find $\underline{u}(A)$;
  3) by bisecting an interval $[u_0, \overline{u}]$ for which $L(u_0) \parallel A < L(\overline{u})$, we find $\overline{u}(A)$.

- Similarly, when we estimate the probability of an event E:
  - we no longer get a single value $ps(E)$;
  - we get an *interval* $\left[\underline{ps}(E), \overline{ps}(E)\right]$ of possible values of probability.

- By using bisection, we can feasibly elicit the values $\underline{ps}(E)$ and $\overline{ps}(E)$.

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20. Decision Making Under Interval Uncertainty

- *Situation:* for each possible decision d, we know the interval $[\underline{u}(d), \overline{u}(d)]$ of possible values of utility.
- *Questions:* which decision shall we select?
- *Natural idea:* select all decisions d_0 that *may* be optimal, i.e., which are optimal for some function

$$u(d) \in [\underline{u}(d), \overline{u}(d)].$$

- *Problem:* checking all possible functions is not feasible.
- *Solution:* the above condition is equivalent to an easier-to-check one:

$$\overline{u}(d_0) \geq \max_d \underline{u}(d).$$

- *Interval computations* can help in describing the range of all such d_0.
- *Remaining problem:* in practice, we would like to select *one* decision; which one should be select?

21. Decisions under Interval Uncertainty: Hurwicz Optimism-Pessimism Criterion

- *Reminder:* we need to assign, to each interval $[\underline{u}, \overline{u}]$, a utility value $u(\underline{u}, \overline{u}) \in [\underline{u}, \overline{u}]$.
- *History:* this problem was first handled in 1951, by the future Nobelist Leonid Hurwicz.
- *Notation:* let us denote $\alpha_H \stackrel{\text{def}}{=} u(0,1)$.
- *Reminder:* utility is determined modulo a linear transformation $u' = a \cdot u + b$.
- *Reasonable to require:* the equivalent utility does not change with re-scaling: for $a > 0$ and b,

$$u(a \cdot u^- + b, a \cdot u^+ + b) = a \cdot u(u^-, u^+) + b.$$

- For $u^- = 0$, $u^+ = 1$, $a = \overline{u} - \underline{u}$, and $b = \underline{u}$, we get

$$u(\underline{u}, \overline{u}) = \alpha_H \cdot (\overline{u} - \underline{u}) + \underline{u} = \alpha_H \cdot \overline{u} + (1 - \alpha_H) \cdot \underline{u}.$$

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22. Hurwicz Optimism-Pessimism Criterion (cont)

- The expression $\alpha_H \cdot \overline{u} + (1 - \alpha_H) \cdot \underline{u}$ is called *optimism-pessimism criterion*, because:
  - when $\alpha_H = 1$, we make a decision based on the most optimistic possible values $u = \overline{u}$;
  - when $\alpha_H = 0$, we make a decision based on the most pessimistic possible values $u = \underline{u}$;
  - for intermediate values $\alpha_H \in (0, 1)$, we take a weighted average of the optimistic and pessimistic values.
- According to this criterion:
  - if we have several alternatives $A', \ldots$, with interval-valued utilities $[\underline{u}(A'), \overline{u}(A')], \ldots,$
  - we recommend an alternative A that maximizes

$$\alpha_H \cdot \overline{u}(A) + (1 - \alpha_H) \cdot \underline{u}(A).$$

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23. Alternative Explanation of the Seemingly Irrational Human Behavior

- *Situation:* an urn contains red (R), green (G), and blue (B) balls; $p(R) = 1/3$.
- *We do not know:* the proportion of green and blue balls, so we only know that $p(G) \in [0, 2/3]$.
- *1st experiment:* choose between two alternatives:

  R: \$1 if a random ball is red, \$0 otherwise;

  G: \$1 if a random ball is green, \$0 otherwise.
- In this case, $u(R) = (1/3) \cdot u(\$1) + (2/3) \cdot u(\$0) = 1/3$.
- Here, $u(G) = p(G) \cdot u(\$1) + (1 - p(G)) \cdot u(\$0) = p(G)$.
- So, possible values of $u(G)$ form an interval $[0, 2/3]$.
- This is equivalent to $\alpha_H \cdot (2/3) + (1 - \alpha_H) \cdot 0 = (2/3) \cdot \alpha_H$.
- Since $G < R$, we have $(2/3) \cdot \alpha_H < 1/3$, so $\alpha_H < 1/2$.

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24. Alternative Explanation (cont-d)

- *2nd experiment:* choose between two alternatives:

GB: \$1 if a random ball is green or blue, \$0 otherwise;

RB: \$1 if a random ball is red or blue, \$0 otherwise.

- *Result:* most people select alternative GB: $RB < RB$.
- Here, $u(GB) = (2/3) \cdot u(\$1) + (2/3) \cdot u(\$0) = 2/3$.
- In this case, $p(RB) = 1 - p(G)$, so

$$u(RB) = (1 - p(G)) \cdot u(\$1) + p(G) \cdot u(\$0) = 1 - p(G).$$

- Since $ps(G) \in [0, 2/3]$, we have $u(RB) \in [1/3, 1]$, which is equiv. to $\alpha_H \cdot 1 + (1 - \alpha_H) \cdot (1/3) = (2/3) \cdot \alpha_H + 1/3$.
- $RB < GB$ means $(2/3) \cdot \alpha_H + 1/3 < 2/3$, i.e., $\alpha_H < 1/2$.
- This is the same restriction on α_H that we obtained from the 1st experiment.

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25. Why Humans Use Quantum-Type Reasoning?

- The authors also speculate on why humans use quantum-type reasoning.
- One possible reason:
  - many real-life processes are quantum, and
  - we want to simulate them.
- Another possible reason:
  - our brain, as a product of billion years of evolution, implements the best possible algorithms, and
  - quantum algorithms are known to be very efficient.

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26. Why Quantum Computing

- The speed of all processes is limited by the speed of light c.
- To send a signal across a 30 cm laptop, we need at least 1 ns; this corresponds to only 1 Gflop.
- If we want to make computers faster, we need to make processing elements smaller.
- Already, each processing cell consists of a few dozen molecules.
- If we decrease the size further, we get to the level of individual atoms and molecules.
- On this level, physics is different, it is quantum physics.
- One of the properties of quantum physics is its probabilistic nature (example: radioactive decay).

27. Why Quantum Computing (cont-d)

- At first glance, this interferes with our desire to make reproducible computations.
- However, scientists learned how to make lemonade out of this lemon.
- First main discovery: Grover's quantum search algorithm.
- To search for an object in an unsorted array of n elements, we need, in the worst case, at least n steps.
- Reason: if we use fewer steps, we do not cover all the elements, and thus, we may miss the desired object.
- In quantum physics, we can find an element in $\sqrt{n}$ steps.
- For a Terabyte database, we get a million times speedup.
- Main idea: we can use superposition of different searches.

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28. Why Quantum Computing (cont-d)

- Another discovery: Shor's cracking RSA coding.
- The RSA algorithm is behind most secure transactions.
- A person selects two large prime numbers P_1 and P_2, and advertises their product $n = P_1 \cdot P_2$.
- By using this open code n, anyone can encode their message.
- To decode this message, one needs to know the factors P_1 and P_2.
- Factoring a large integer is known to be a computationally difficult problem.
- It turns out that with quantum computers, we can factor fast and thus, read all encrypted messages.
- The situation is not so bad: there is also a quantum encryption which cannot be easily cracked.

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