Axiomatic foundations of economics

2017 Shanghai Neuroeconomics Summer School

July 16, 2017

I will talk about:

- Value, utility and subjective value
- Cardinal and ordinal utility
- Revealed preference (axiomatic) approach
- Expected Utility Theory
- Empirical approaches to estimating preference
- Axiomatic approaches in neuroeconomics (XXI)

Expected Value

- Pascal (XVII century) suggested a theory to explain how we should calculate payoffs for the players that could not finish the game
- Imagine a game with two possible outcomes x and y. How much is this game worth?
- If each outcome is equaly likely, then the expected value of this game is $\frac{x+y}{2}$
- The expected value (EV) of receiving x with probability p is given by:

$$EV = p * x$$

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$$EV(belive) = p\infty + (1-p)l = \infty$$
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You should choose the option with higher EV, so believe.

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But do people really maximise expected *value*?
Will they be better off by maximizing expected value?
Should we be advising people to maximize expected value?

St. Petersburg paradox

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- **You**: You were willing to pay significantly less

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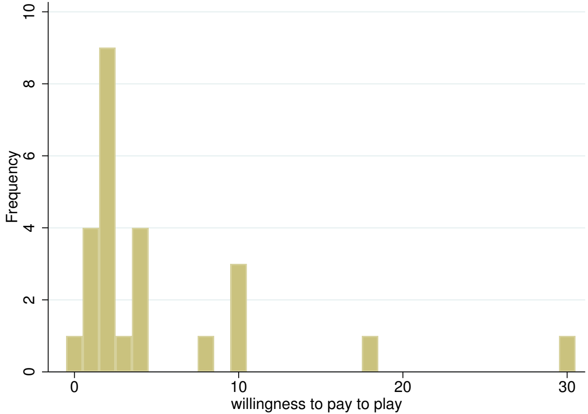

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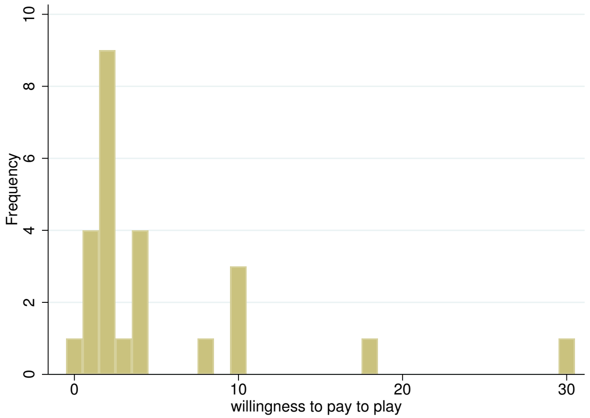

- One person offered 400CNY
- Are you "bad" decision-makers?

Bernoulli's Logarithmic Utility (1738)

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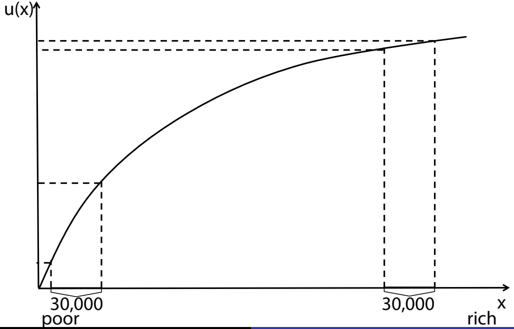
- But would there be any trade?
  - Yes, if people have different wealth!
    "There is no doubt that a gain of one thousand ducats is more significant to the pauper than to a rich man though both gain the same amount."

Bernoulli's Logarithmic Utility (1738)

- Bernoulli's key insights:
  - He replaced value with utility - people maximise utility not value!
  - How much utility you gain from additional x depends on wealth $u(w+x)$
  - Bernoulli suggested that utility is logarithmic and defined over final wealth
    $u(w+x) = log(w+x)$



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- Imagine the beggar has only \$100 in his pocket
  $u(sell) = log(100 + 30,000) = 10.31$
  $u(keep) = 0.25 log(100 + 200,000) + 0.75 log(100) = 6.51$
  $u(sell) > u(keep)$ so the beggar should sell!
- Any person with wealth level higher than approximately \$90,000 would be better off keeping the lottery ticket

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- Bernoulli also predicts that the higher your wealth, the more you are willing to pay to play the game (and this is the only factor explaining differences between individuals)

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  - Is utility function indeed logarithmic?
  - Should probability be multiplied by utility from the reward?
  - Do people perceive likelihoods of events objectively?

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- This model fits data better than Pascal's expected value, but ...
  - Is utility function indeed logarithmic?
  - Should probability be multiplied by utility from the reward?
  - Do people perceive likelihoods of events objectively?
- In response to these criticisms many mathematical functions were tried
- Additional parameters were added to these functions to improve empirical fit (sounds familiar?)

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- Remember the goal of the economists was to advise and change policy to improve welfare (net utilities)
  - through changes in taxation, subsidies for example
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- A group of economists begun to worry that highly unstructured and ad hoc models are used to influence policy

Towards revealed preference

- Economic theory took a turn in response to the following concerns:
  - we don't even know if utility exists
  - we do not know if people maximise
  - we can't observe utility, only choice - what if the choice was a mistake (not the best option)?
  - even if utility exists, we cannot compare it across or even within individuals!

Pareto - utility is ordinal (1906)

- Suppose you have the following preferences:
  - dumplings $\succ$ chow mein
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  - So are you three times or twice happier with dumplings instead of chow mein?

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- I can square these numbers, double them, subtract x from them and still be able to rationalise these preferences
- Pareto showed that the precise numerical scaling of utilities is almost unconstrained by the data on choices and prices. And thus meaningless for making welfare statements
- The numbers are meaningless then for anything other than telling what is preferred to what
  - We can't say that you like dumplings twice as much as chow mein, only that you like them more

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- Utility of a particular good or service cannot be measured using a numerical scale bearing economic meaning
  - Compare $, effort, pain
- Goods can only be ordered such that one is considered by an individual to be worse than, equal to, or better than the other
- Choices tell us rankings, not utilities!
- Utility is ordinal, not cardinal.

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- So how do we choose policy?
  - Allocation is *pareto optimal* if it is impossible to make any one individual better off without making at least one individual worse off

New criteria for a good models of choice

- A good model assumes almost nothing (for sure not a functional form)
- All assumptions should be testable
- Models should be based on observables only (so that they can be falsified if untrue - so ordinal theory is testable too)
- We cannot exactly predict u from observing choice
- But we can infer your preferences from observing your choices
- If we observed u we could exactly predict choice (but we don't observe u)
- The goal: use choice to derive theory from scratch
- Instead of utility causing choice, make the theory about the choice

Weak Axiom of Revealed Preference

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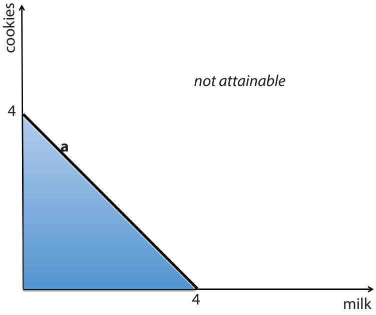
  - but I cannot strictly prefer B over A ($B \succ A$)
- **Samuelson proved that anybody who violates WARP, cannot be described with a single utility function** (necessary condition for utility representation)

Revealed preference: WARP graphically

Steve is deciding how many cookies and milk he wants
Budget constraint: $p_c * x_c + p_m * x_m \leq \$20$

- Budget line: $x_c = \frac{20 - p_m * x_m}{p_c}$, here: $p_c = p_m = \$5$



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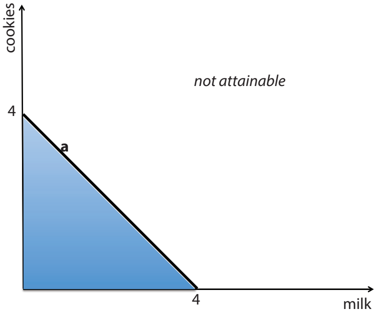

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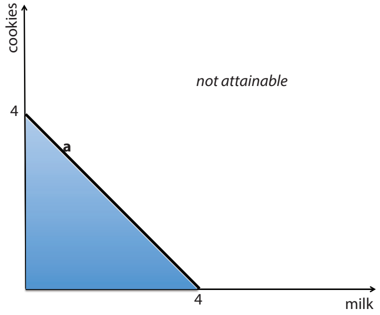

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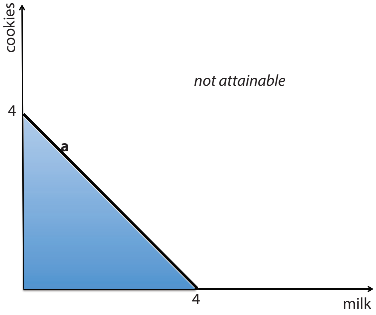

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Suppose Steve chooses within blue triangle (not on the budget line):

- He is not maximising utility
- He has non-monotonic utility

Revealed preference: WARP violation numerically

- Can you tell if Bob's choices can be represented with utility function?

scenario	p_A	p_B	x_A	x_B	c_1	c_2	c_3
1	\$1	\$2	1	2			
2	\$2	\$1	2	1			
3	\$1	\$1	2	2			

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  - Scenario 3: $3 \succ 1$ and $3 \succ 2$

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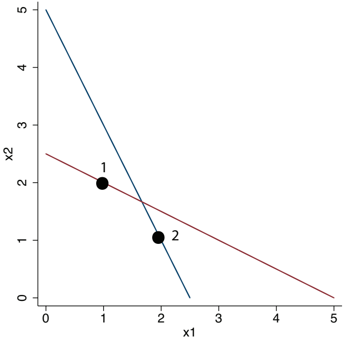
  - Scenario 3: $3 \succ 1$ and $3 \succ 2$
  - Scenario 2: $2 \succ 1$
  - Scenario 1: $1 \succ 2$
  - Bob's choices cannot be described by a utility function!

Revealed preference: WARP violation graphically

- Suppose Bob has \$5
- Scenario 1: $p_A = \$1$ and $p_B = \$2$, selected (1,2)
- Scenario 2: $p_A = \$2$ and $p_B = \$1$, selected (2,1)



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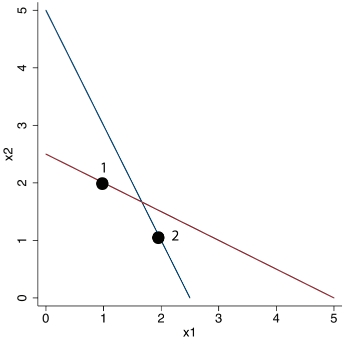

- It would be convenient to have a necessary condition for utility representation

Revealed preference: WARP refinements - GARP

- **Generalized Axiom of Revealed Preference (GARP)**, Houthakker (1950)
  If $A \succeq B$ and $B \succeq C$, then $A \succeq C$ (transitive preferences)
- GARP is **necessary and sufficient** condition for utility maximisation
- If GARP is passed, then individual's behaviour is describable with some utility function (!)
- Utility is back
- We can test whether choice is rational
- Economists have a very precise definition of rationality
- Being irrational = violating GARP (inconsistent preferences)

GARP as rationality test: example

- Suppose Nathaniel tells me that his preferences are: $wine \succ beer$, $beer \succ vodka$ and $vodka \succ wine$

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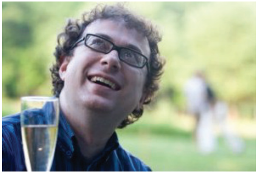
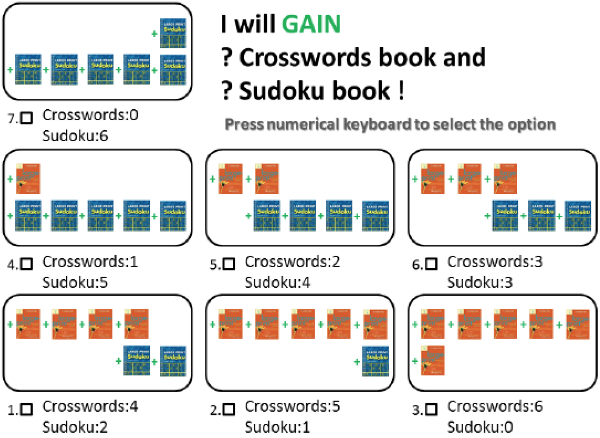


GARP as rationality test - Harbaugh, 2001 design



Chung, Tymula and Glimcher, 2017

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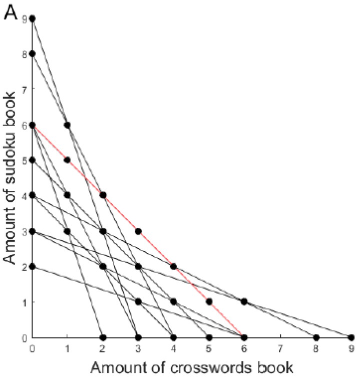

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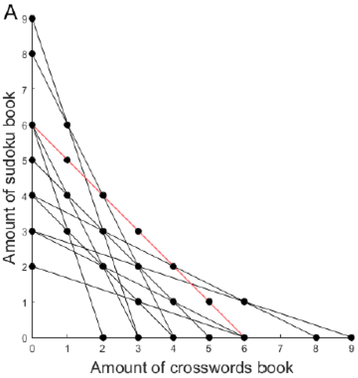

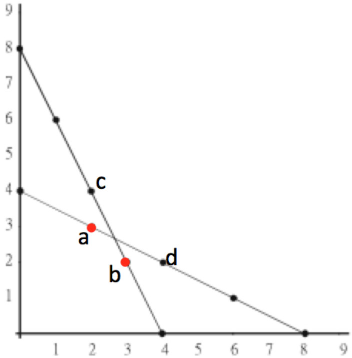

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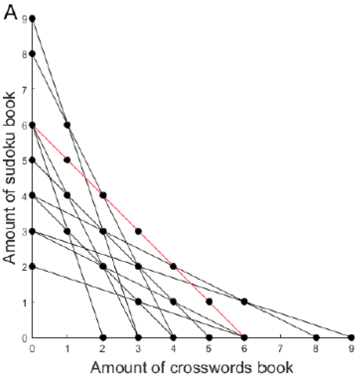

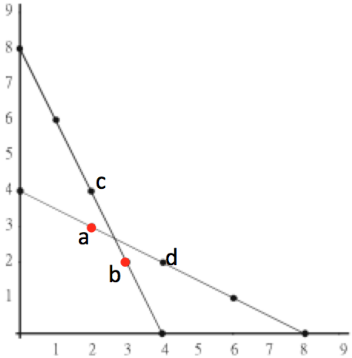

- **u(a)** $> u(d)$ (choice)

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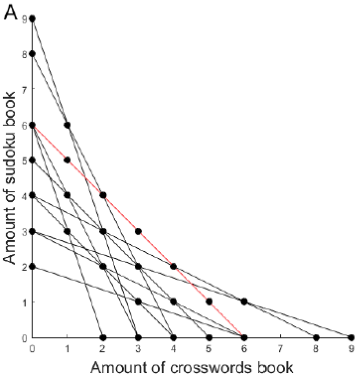

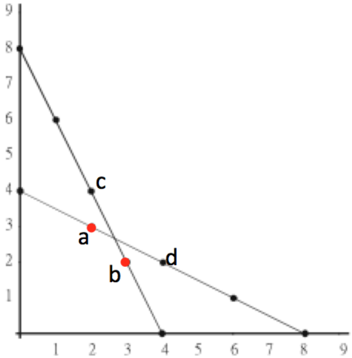

- $\mathbf{u(a)} > u(d)$ (choice)
- $u(d) > u(b)$ (monotonicity)

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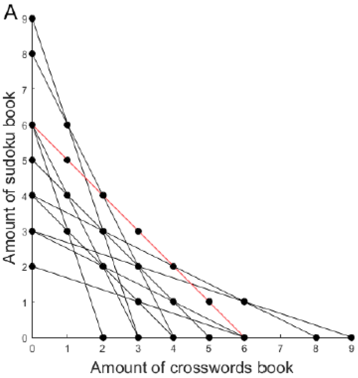

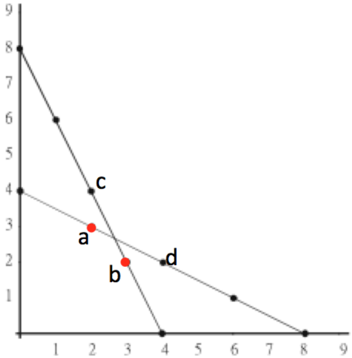

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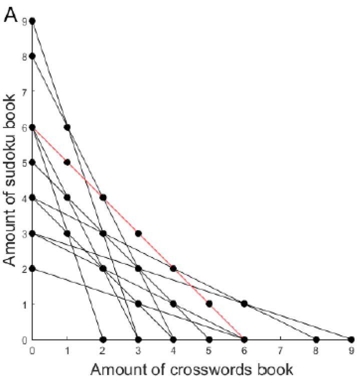

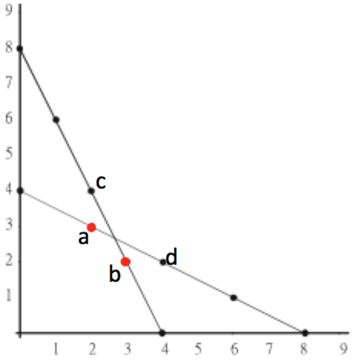

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GARP as rationality test

- In (really) drunk people
  - Burghart, D.R., Glimcher, P. W., and Lazzaro, S.C. (2013). An Expected Utility Maximizer Walks Into A Bar... Journal of Risk and Uncertainty, 46(3)
- In kids
  - Harbaugh, W.T., Krause, K., Berry, T. (2001). GARP for kids: on the development of rational choice behavior. American Economic Review, 91(5), 1539-1545
- Altruism
  - Andreoni, J., & Miller, J. (2002). Giving according to GARP: an experimental test of the consistency of preferences for altruism. Econometrica, 70(2), 737-753

GARP as rationality test

- In subjects with damage to ventromedial frontal lobe
  - Camille et al. (2011). Ventromedial Frontal Lobe Damage Disrupts Value Maximization in Humans. Journal of Neuroscience, 31(20), 7517-7532
- Throughout menstrual cycle
  - Lazzaro SC, Rutledge RB, Burghart DR, Glimcher PW (2016) The Impact of Menstrual Cycle Phase on Economic Choice and Rationality, PLoS ONE
- Rationality neurocorrelates (ventrolateral prefrontal cortex) in older adulthood (and in dementia)
  - Chung H., Tymula A., Glimcher P. (2017), r&r
- In mood disorders (in progress)
  - Weinrabe A., Chung H., Tymula A., Hickie I.

Axiomatic approach: advantages & disadvantages

- Very general: for economist, you can be rational even if *licorice* $\succ$ *spinach*, *spinach* $\succ$ *bananas* and *licorice* $\succ$ *bananas*
- Doesn't tell us how the utility looks like but that it exists
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- Doesn't tell us how the utility looks like but that it exists
- But if utility does not exist, then you could look for it endlessly and would not find the right one
- Important: any monotonic transformation of utility numbers preserves choice ordering and thus preserves compliance with GARP
  - So we don't know how much one good is better than other. The magnitude is not constrained, only the order is
- Revealed preference approach dominates economic theory since its inception

Revealed preference approach

- The standard for good economic model:
  - The model has concise statements (axioms) that:
    - are easy to understand
    - can be tested
  - Mathematical proof relates these axioms to a clear theory of value or utility
  - Falsifying an axiom falsifies a whole group of theories that rest on it
  - It uses choices to derive utility (not the other way round)
    - Compare to Pascal's approach

Revealed preference approach

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Revealed preference approach

- Problem: 27% of \$50,000 very different from 28% of \$50,000
- Solution: Expected utility theory of decision-making under risk

Revealed preference approach

- We so far learned about preferences and utilities over sure outcomes
- Utility representation exists when preferences are rational (satisfy GARP)
  For example, it cannot be that $a \succ b \succ c \succ a$
- But most of the decisions we make involve uncertainty
- How to represent preferences over uncertain outcomes?

Expected Utility Theory

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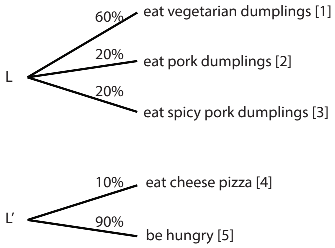
- You are choosing between two lotteries:
  L - eat the dumplings, and
  L' - do not eat the dumplings

Expected Utility Theory



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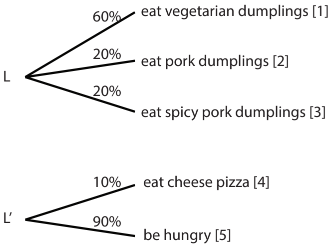

- 5 possible outcomes, $i = 1, 2, 3, 4, 5$
- Corresponding probabilities p_1, p_2, p_3, p_4, p_5
  - p_i - probability that outcome i occurs
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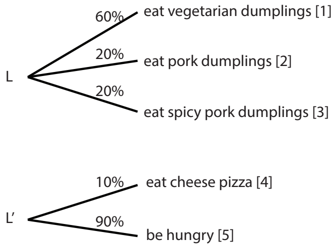

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- Bernoulli: choose L if $U(L) > U(L')$
  $U(L) = p_1 u_1 + p_2 u_2 + p_3 u_3$
  $U(L') = p_4 u_4 + p_5 u_5$

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- So when we add uncertainty, not only ranking (ordinal utility) matters, but also the magnitude of the utility numbers
- Utility function that would work is for example $u_1 = 27,\ u_2 = 8$ and $u_3 = 1$

Expected Utility Theory

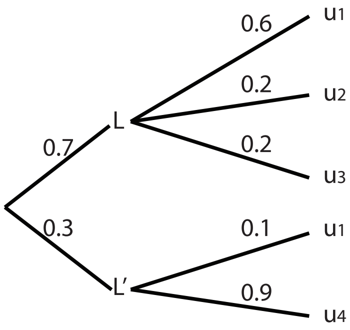
- It is not always possible to find u that would account for the lottery ranking
- We need new assumptions over preferences over lotteries to know if there is U representation over lottery preferences
- von Neumann and Morgenstern (1944) - new theory of value using neoclassical approach
  - They wanted to understand strategic behaviour: how do you react to others when their actions are uncertain?
- So far there is no way to think of similar probabilistic outcomes as related, e.g. 9% of apple and 8% of apple

Expected Utility Theory: Axioms

- **Completeness**:
  For any L and L', either $L \succ L'$ or $L' \succ L$ or $L \sim L'$
  - The individual has well defined preferences and can always decide between any two alternatives
- **Transitivity**:
  If $L \succeq L'$ and $L' \succeq L''$, then $L \succeq L''$
  - The individual decides consistently

Expected Utility Theory: Axioms

- To understand the next axioms we need to understand the idea of a compound lottery (probability distribution over lotteries - outcome of a lottery is another lottery)



$$p_1 = 0.7 * 0.6 + 0.3 * 0.1$$

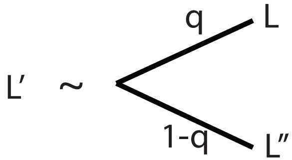
$$p_2 = 0.7 * 0.2$$

$$p_3 = 0.7 * 0.2$$

$$p_4 = 0.3 * 0.9$$

Expected Utility Theory: Axioms

- **Continuity**:
  If $L \succeq L' \succeq L''$, then there exists a unique probability q such that: $L' \sim qL + (1-q)L''$



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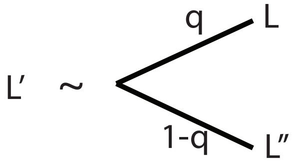

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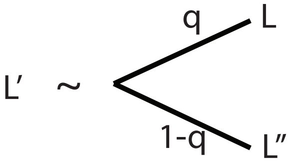

  - Ensures that small changes in probability do not cause large changes in preference ordering
  - Canonical objection $X = \$10,000; 0; \textit{death}$. Does q such that $L' = [0,1,0] \sim [q,0,1-q] = L$ really exist?
    - On the other hand, we encounter some probability of dying all the time

Expected Utility Theory: Axioms

- **Independence**:
  If $L \succeq L'$, then $qL + (1-q)L'' \succeq qL' + (1-q)L''$, where c is the third lottery and q is a number between 0 and 1
  - Your preference over two lotteries isn't affected by mixing in the third

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  - This is the axiom that microeconomists find most problematic and worked on the most
  - Allais paradox, overweighting of small probabilities are examples of violations of independence

Theorem

If preferences satisfy completeness, transitivity, continuity and independence, then it is possible to assign a real number (utility) u_i *to each outcome* $i = 1, 2, ..., n$
such that $L \succeq L'$ *if and only if* $U(L) \geq U(L')$,
where $U([p_1, p_2, ..., p_n]) = p_1 u_1 + p_2 u_2 + ... + p_n u_n$

- Theorem tells us that von Neumann and Morgenstern (vNM) utility exists but not what it is

Expected Utility Theory

- Is the vNM utility unique?

Expected Utility Theory

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- Suppose u and v are both vNM utility functions

	x_1	x_2	x_3
u	3	2	1
v	27	8	1

- u and v represent the same preference ordering $x_1 \succ x_2 \succ x_3$
- v is an increasing transformation of u, $v(x_i) = (u(x_i))^3$
- Can v be used as the same vNM function as u?

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- Imagine two lotteries: $L = [0, 1, 0]$ and $L' = [0.3, 0, 0.7]$

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- Imagine two lotteries: $L = [0, 1, 0]$ and $L' = [0.3, 0, 0.7]$
  - $u(L) > u(L')$
    - $u(L) = 2$
    - $u(L') = 0.3 * 3 + 0.7 * 1 = 1.6$
  - $v(L) < v(L')$
    - $v(L) = 8$
    - $v(L') = 0.3 * 27 + 0.7 * 1 = 10$

- Suppose u and w are both vNM utility functions

	x_1	x_2	x_3
u	3	2	1
w	14	10	6

- u and w represent the same preference ordering $x_1 \succ x_2 \succ x_3$
- w is an increasing transformation of u, $w(x_i) = 4u(x_i) + 2$
- Imagine two lotteries: $L = [0, 1, 0]$ and $L' = [0.3, 0, 0.7]$
  - $u(L) > u(L')$
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  - $w(L) > w(L')$
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    - $w(L') = 0.3 * 14 + 0.7 * 6 = 8.4$

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  - $w(L) > w(L')$
    - $w(L) = 10$
    - $w(L') = 0.3 * 14 + 0.7 * 6 = 8.4$
- A theorem says that w can be used as the same vNM function as u

Expected Utility Theory

Theorem

Suppose u is a vNM function for some preference ordering. v is a vNM function for the same ordering if and only if there exists $a > 0$ and $b \in R$ such that $v(x_i) = au(x_i) + b$ for every i.

- vNM utility functions are ordinal not cardinal, even though there are more restrictions imposed than by GARP
- Utility is still only relative measurement
- It is not a physical measurement that makes cardinal sense

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- vNM utility functions are ordinal not cardinal, even though there are more restrictions imposed than by GARP
- Utility is still only relative measurement
- It is not a physical measurement that makes cardinal sense
- What does it have to do with neuroeconomics?

Subjective Expected Utility

- Expected utility assumes that the distribution of uncertainty is known objectively
  - But this is rarely the case in real life
- It would be extremely helpful (for theory and practice) if we could say that people
  - make choices as if they held probabilistic beliefs
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  - their beliefs could be revealed by their behaviour
- Savage's framework (1954): **necessary and sufficient** conditions for the existence of expected utility maximisation with subjective probabilities

Subjective Expected Utility: framework

- There are different states of the world, S, - resolutions of uncertainty, e.g. it will rain or not
- There is a set of consequences, X, e.g. I am wet or dry
- There is a set of acts A that map from S to X

  A: umbrella, **no umbrella**

  S: **rain**, no rain

  X: **I am wet**, I am dry
- The decision-maker has a preference relation over acts
  - has valuation of consequences by utility function $u(X)$
  - has probabilistic beliefs over the likelihood of all states $p(S)$
  - has preferences over acts by taking expectations of utility with respect to subjective probability

Subjective Expected Utility Axioms

1. The preference relation is transitive and complete
2. "Sure thing principle" - sure things, that happen regardless of the action chosen, should not affect one's preferences
3. Ordinal ranking of consequences is independent of the state and the act that yields them
4. Betting preferences are independent of the specific consequences that define bets
5. The decision maker is not indifferent among all acts
6. No consequence is either infinitely better or worse than any other consequence (continuity)
7. If the decision maker considers an act strictly better (worse) than each of the payoffs of another act on a given event, then the former act is conditionally strictly (less) preferred than the latter

From Edi Karni's *Savages' Subjective Expected Utility Model, 2005*

Subjective Expected Utility Axioms

Theorem

A preference relation that satisfies axioms 1-7 is equivalent to the maximisation of the expectations of a utility function on the set of consequences with respect to a probability measure on the set of all events.

EUT famous criticisms: Allais Paradox

(S)EUT is normatively very attractive but people repeatedly violate some of the axioms

$$A \succ B \qquad\qquad D \succ C$$

$$u(1) > 0.01u(0) + 0.89u(1) + 0.1u(5) \qquad\qquad 0.11u(1) + 0.89u(0) < 0.1u(5) + 0.9u(0)$$

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$A \succ B$ $\quad\quad$ $D \succ C$

$$u(1) > 0.01u(0) + 0.89u(1) + 0.1u(5)$$

$$0.11u(1) + 0.89u(0) < 0.1u(5) + 0.9u(0)$$

$$0.11u(1) > 0.01u(0) + 0.1u(5)$$

$$0.11u(1) < 0.1u(5) + 0.01u(0)$$

EUT famous criticisms: Allais Paradox

- Allais Paradox presents a violation of the independence axiom
- Allais point: there may be complementarities between the outcomes in the gambles - one does not evaluate gamble A independently of gamble B
- Various theories have been suggested to overcome this problem:
  - prospect theory by Kahneman and Tversky,
  - rank-dependent expected utility by Quiggin,
  - regret theory

EUT famous criticisms: Allais Paradox

- Only three of you (3/26) violated Allais paradox
- $B(23) \succ A(3)$ and $D(26) \succ C(0)$

SEU famous criticisms: Ellsberg Paradox

There is an urn with 300 balls: 100 red and 200 either blue or green (so not all probabilities are objectively known)

- Which gamble do you prefer?
  - A: Win \$1,000 if red
  - B: Win \$1,000 if blue
  - People $A \succ B$
- Which gamble do you prefer?
  - C: Win \$1,000 if not blue
  - D: Win \$1,000 if not red
  - People $D \succ C$
- Such preferences are inconsistent with SEU

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- Such preferences are inconsistent with SEU
- $A \succ B$ iff
  $p(r)u(1) + (1 - p(r))u(0) > p(b)u(1) + (1 - p(b))u(0)$
- $D \succ C$ iff
  $(1 - p(r))u(1) + p(r)u(0) > (1 - p(b))u(1) + p(b)u(0)$
- $u(1) + u(0) > u(1) + u(0)$

SEU famous criticisms: Ellsberg Paradox - Your choices

There is an urn with 300 balls: 100 red and 200 either blue or green (so not all probabilities are objectively known)

SEU famous criticisms: Ellsberg Paradox - Your choices

There is an urn with 300 balls: 100 red and 200 either blue or green (so not all probabilities are objectively known)

- Most of you, 17/26 students, violated SEU

SEU famous criticisms: Ellsberg Paradox - Your choices

There is an urn with 300 balls: 100 red and 200 either blue or green (so not all probabilities are objectively known)

- Most of you, 17/26 students, violated SEU
- $A(18) \succ B(8)$
- $D(23) \succ C(3)$

Preference measurement

Preference measurement

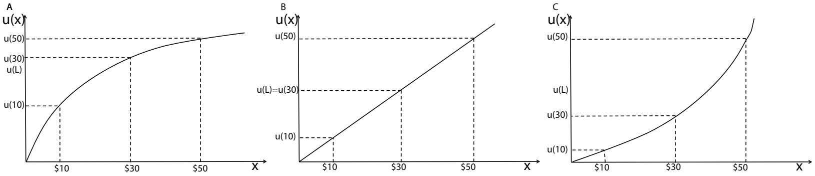
$$U(x, p, t) = D(t)w(p)u(x) + \epsilon$$

Preference measurement

$$U(x, p, t) = D(t)w(p)u(x) + \epsilon$$

- Risk preference
- Probability weighting
- Time preference
- Loss aversion
- Randomness

- Risk preference = utility curvature



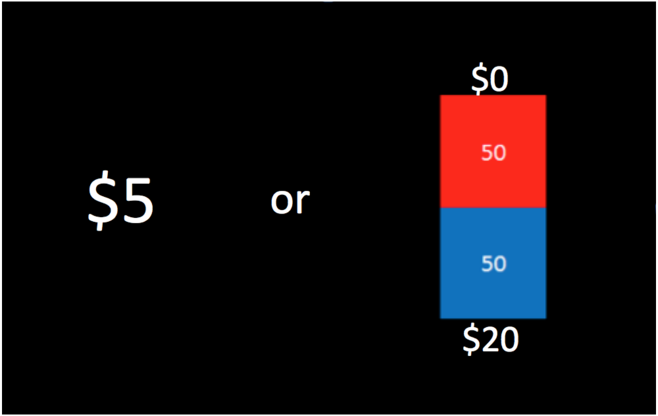
risk averse　　　　risk neutral　　　　risk seeking

- Methods: find certainty equivalent of a gamble: $p * u(x) = c$
- James C. Cox, Glenn W. Harrison (ed.) Risk Aversion in Experiments: Research in Experimental Economics, 2008, Volume 12, Emerald Group Publishing Limited

- One choice at a time

Preference measurement - risk attitude

- One choice at a time



- Price list (Holt and Laury, 2002)

TABLE 1—THE TEN PAIRED LOTTERY-CHOICE DECISIONS WITH LOW PAYOFFS

Option A	Option B	Expected payoff difference
1/10 of \$2.00, 9/10 of \$1.60	1/10 of \$3.85, 9/10 of \$0.10	\$1.17
2/10 of \$2.00, 8/10 of \$1.60	2/10 of \$3.85, 8/10 of \$0.10	\$0.83
3/10 of \$2.00, 7/10 of \$1.60	3/10 of \$3.85, 7/10 of \$0.10	\$0.50
4/10 of \$2.00, 6/10 of \$1.60	4/10 of \$3.85, 6/10 of \$0.10	\$0.16
5/10 of \$2.00, 5/10 of \$1.60	5/10 of \$3.85, 5/10 of \$0.10	−\$0.18
6/10 of \$2.00, 4/10 of \$1.60	6/10 of \$3.85, 4/10 of \$0.10	−\$0.51
7/10 of \$2.00, 3/10 of \$1.60	7/10 of \$3.85, 3/10 of \$0.10	−\$0.85
8/10 of \$2.00, 2/10 of \$1.60	8/10 of \$3.85, 2/10 of \$0.10	−\$1.18
9/10 of \$2.00, 1/10 of \$1.60	9/10 of \$3.85, 1/10 of \$0.10	−\$1.52
10/10 of \$2.00, 0/10 of \$1.60	10/10 of \$3.85, 0/10 of \$0.10	−\$1.85

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- Potential problem: imperfect identification if individuals do not perceive probabilities objectively

Preference measurement - subjective probabilities

- Estimation methods: Bruhin et al. 2010; Conte et al. 2011; Harrison & Rutstrm 2009; Hey & Orme 1994; Abler et al. 2006; Harbaugh et al. 2002; Harrison & Rutstrm 2009; Wilcox 2015; Prelec & Loewenstein 1998; Fox & Poldrack 2014
  - For utility-free elicitation, see Abdellaoui 2000
- Neuro evidence: Abler et al. 2006; Berns et al. 2008; Preuschoff, Bossaerts, and Quartz 2006; Tobler et al. 2008; Hsu et al. 2009

Preference measurement - time preference

- Types of discount functions:
  - Temporarily consistent chooser
    - Exponential discounting
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    - Quasihyperbolic discounting

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- Measurement:

$$\$X \text{ sooner or } \$Y \text{ later, where } \$X < \$Y$$

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- Useful reference:
  - Cheung S. (2016) Recent developments in the experimental elicitation of time preference J Behav Exp Finance, Vol 11: 1-8

Preference measurement - loss aversion

- The most commonly used utility specification:

$$U(x) = \begin{cases} u_g(x) & \text{if } x \geq 0 \\ \lambda u_l(x) & \text{if } x < 0 \end{cases}$$

  where λ - loss aversion
- Estimating λ requires:
  - : Gamble certainty equivalent / utility curvature in gains
  - : Gamble certainty equivalent / utility curvature in losses
  - : Mixed (gain-loss) gambles to estimate loss aversion
- Evidence on λ is quite messy

Axiomatic approach in neuroeconomics

Axiomatic approach in neuroeconomics

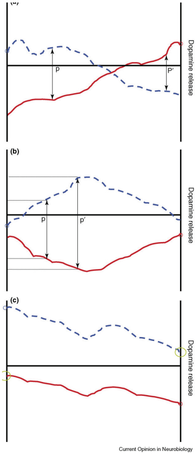
- Caplin, Dean, Glimcher and Rutledge used revealed preference approach to study dopamine
- Dopamine plays crucial role in behaviour (neurotransmitter = carries information form one cell to another)
- Dopaminergic reward prediction error (RPE) hypothesis: neurons that contain dopamine release it in proportion to:

  experienced reward-predicted reward

- H: the role of dopamine is to update the value attached to options
- Problems:
  - data consistent with other hypothesis ("incentive salience", "attention switching", "surprise")
  - RPE similar to early economic choice theory: unobservable reward mediates relationship between dopamine, stimuli and choice
- Goal: identify whether the dopamine system encodes RPE **from the observables**

Axiomatic approach in neuroeconomics

- A1: Ranking of different prizes is independent of the lottery that prizes are received from
- A2: Ranking of lotteries must be independent of the prizes received from those lotteries
- A3: If prize is fully anticipated then dopamine activity has to be independent of what the prize is



Axiomatic approach in neuroeconomics

Theorem

The three axioms above are necessary and sufficient for the RPE model.

- Note: this does not imply that RPE model is the only one that satisfies the three axioms

Axiomatic approach in neuroeconomics

- Rutledge et al. (2010) tested the RPE hypothesis using these axioms
- Neural activity in striatum, medial prefrontal cortex, amygdala and posterior cingulate cortex is consistent with the RPE model
- Activity in the anterior insula falsifies the axiomatic model of RPE
- For other example, see Steverson, Brandenburger and Glimcher (2016)

THE END