Optimization Models for Social Justice

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CPAIOR Master Class

June 2019

Modeling Social Justice

- **Social welfare** is more than overall benefit.
  - Also concerns **equity** or **just distribution** of resources.
  - Not obvious how to capture equity in the **objective function**.
  - Still less obvious how to **combine** it with total benefit.

Modeling Social Justice

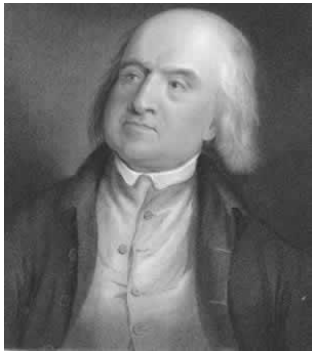
- Some problem areas…
  - Health care resources.
  - Facility location (e.g., emergency services).
  - Taxation (revenue vs. progressivity).
  - Relief operations.
  - Telecommunications (leximax, Nash bargaining solution)

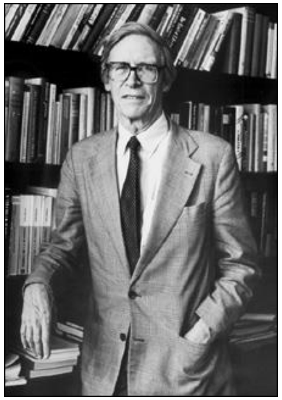
Outline

- Utilitarianism
- Rawlsian Difference Principle
- Axiomatics
- Measures of Inequality
- A Fair Division Problem
- Nash Bargaining Solution
- Raiffa-Kalai-Smorodinsky Bargaining
- Combining Equity and Utility
- Health Care Example
- References

Utility vs. Equity

- Two classical criteria for distributive justice:
  - **Utilitarianism (total benefit)**
  - **Difference principle** of **John Rawls (equity)**
- These have the must studied philosophical underpinnings.





Utilitarianism

- **Utilitarianism** seeks allocation of resources that maximizes total utility.
  - Let x_i = resources allocated to person *i*.
  - Let $u_i\,(x_i)$ = utility enjoyed by person *i* receiving resources x_i
  - We have an optimization problem

$$\max \sum_i u_i(x_i)$$

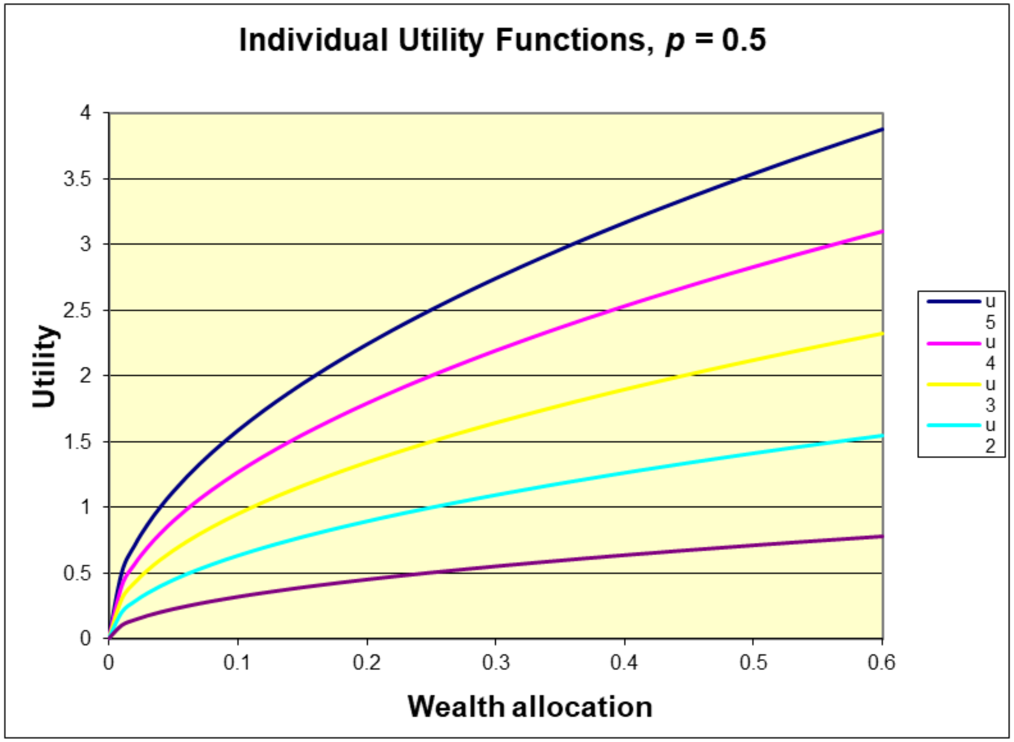
Utility (production) functions

$$x \in S$$

Set of feasible resource allocations

Utilitarianism

For example, $h_i(x_i) = a_i x_i^p$ with different a_i's for 5 individuals



Utilitarianism

Assume resource distribution is constrained only by a fixed budget.

If $u_i(x_i) = a_i x_i^p$, we have the optimization problem

$$\max \sum_i a_i x_i^p$$

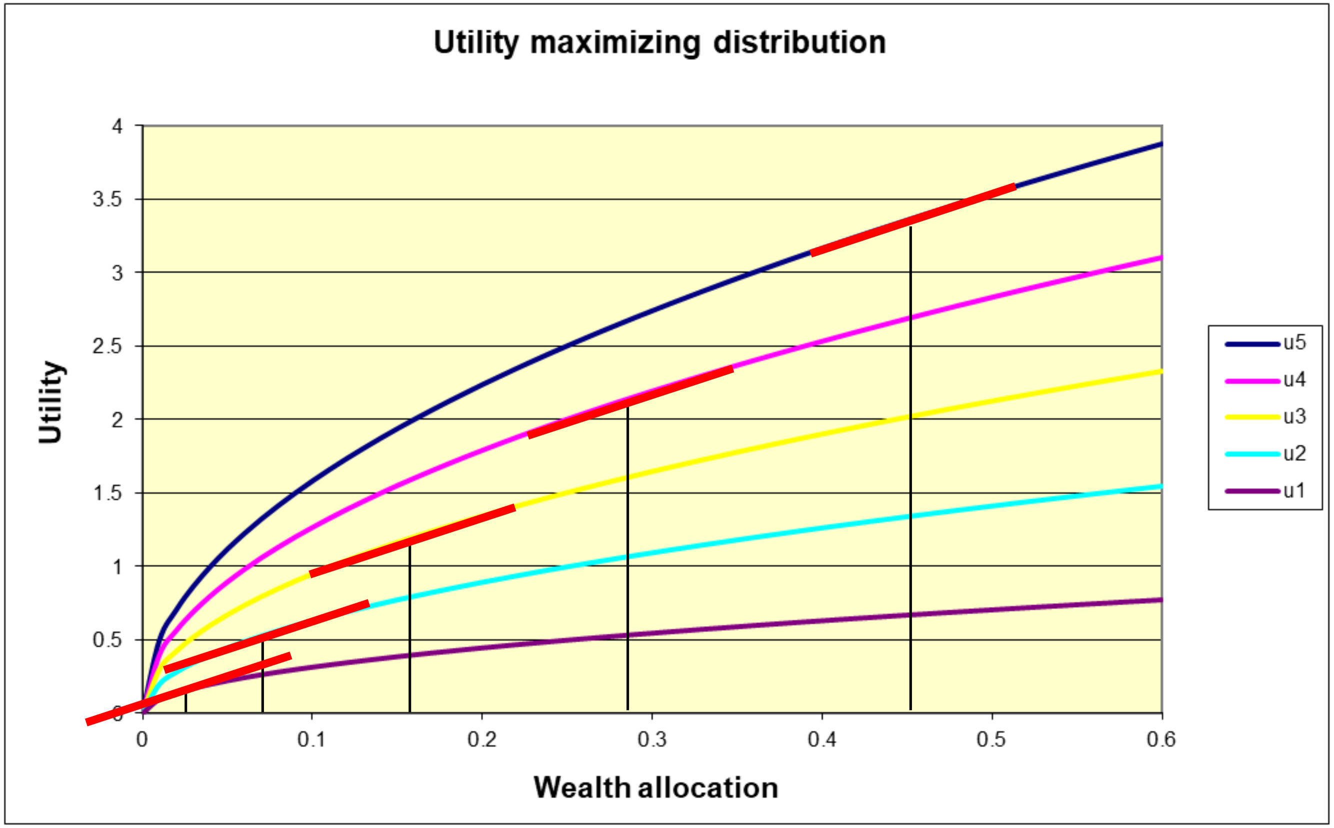
$$\sum_i x_i = 1, \ x_i \geq 0, \ \text{all } i$$

This has a closed-form solution

$$x_i = a_i^{\frac{1}{1-p}} \left(\sum_{j=1}^{n} a_j^{\frac{1}{1-p}} \right)^{-1}$$

Utilitarianism

Optimal allocations equalize slope (i.e., equal marginal utility).

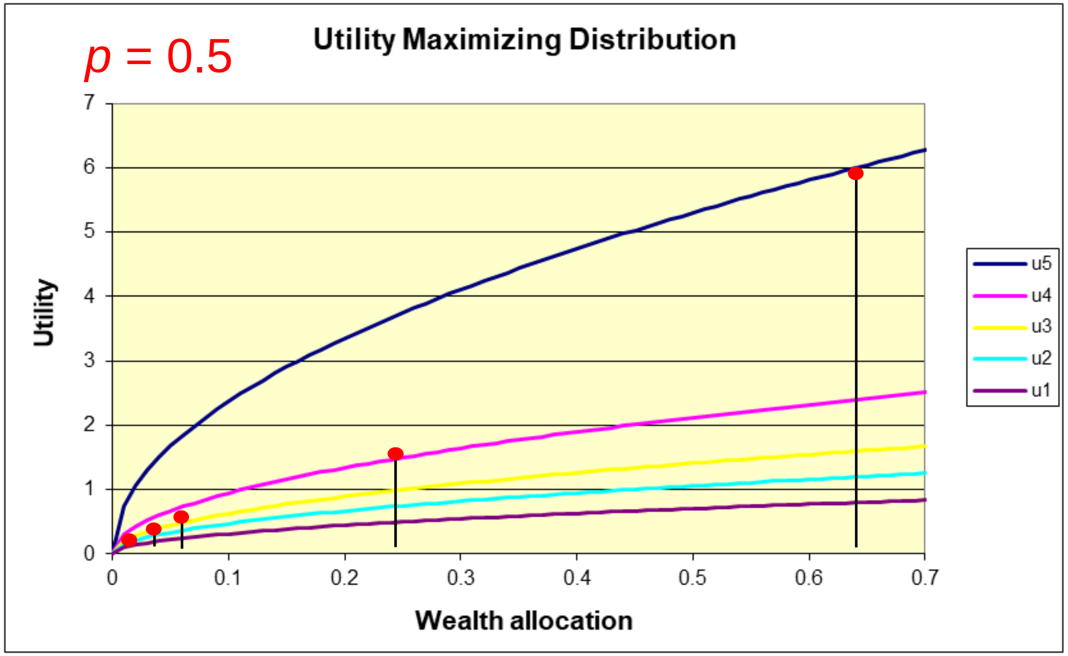


Utilitarianism

- **Arguments for utilitarianism**
  - Can define utility to suit context.
  - Utilitarian distributions incorporate some **egalitarian** factors:
  - With **concave** utility functions, egalitarian distributions tend to create more utility.
  - Inegalitarian distributions create **disutility**, due to social disharmony.

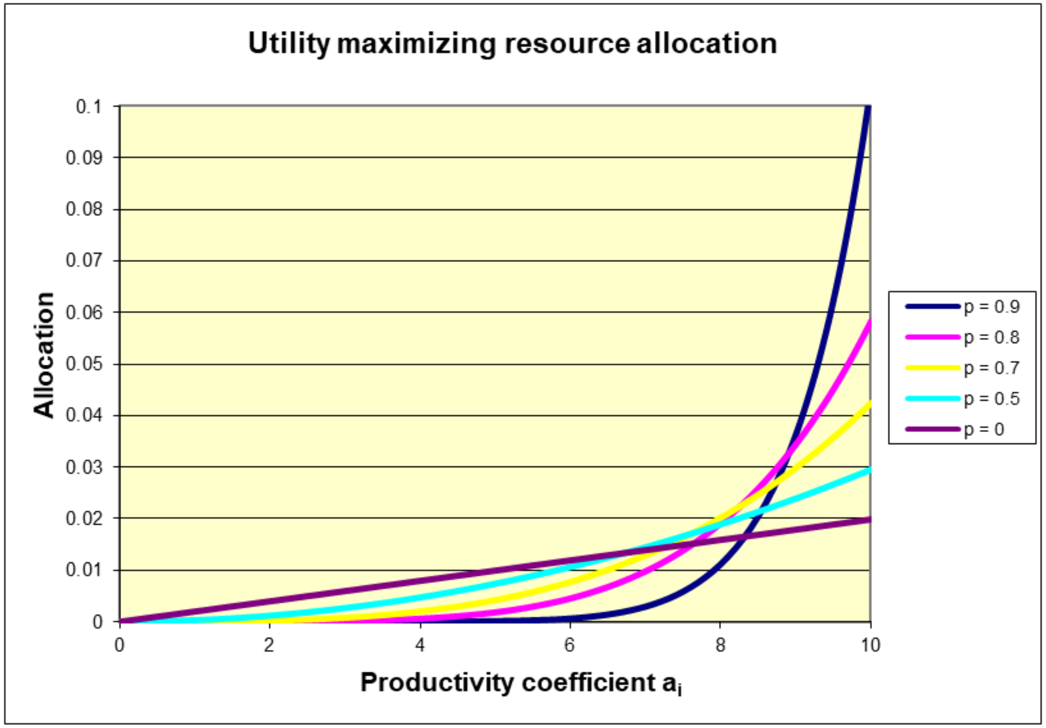
Utilitarianism

- Egalitarian distributions create more utility?
  - This effect is **limited**.
  - Utilitarian distributions can be very unequal. Productivity differences are magnified in the allocations.



Utilitarianism

- Egalitarian distributions create more utility?
  - In the example, the **most egalitarian** distribution ($p \rightarrow 0$) assigns resources in proportion to individual utility coefficient.



Utilitarianism

- Unequal distributions create disutility?
  - Perhaps, but modeling this requires **nonseparable** utility functions

$$u_i(x_1,\cdots,x_n)$$

that may result in a problem that is hard to model and solve.

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  - More fundamentally, this defense of utilitarianism is based on **contingency**, **not principle**.

Utilitarianism

- Unequal distributions create disutility?
  - Perhaps, but modeling this requires **nonseparable** utility functions

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    that may result in a problem that is hard to model and solve.
  - More fundamentally, this defense of utilitarianism is based on **contingency**, **not principle**.
  - If we can **evaluate** the fairness of utilitarian distribution, then there must be **another standard** of equitable distribution.
  - How do we model the standard we really have in mind?

Utilitarianism

- To sum up: A utility maximizing distribution may be unjust.
  - Disadvantaged people may be neglected because they gain less utility per unit of resource.

Rawlsian Difference Principle

- Rawls' **Difference Principle** seeks to maximize the welfare of the worst off.
  - Also known as **maximin** principle.
  - Another formulation: inequality is permissible only to the extent that it is necessary to improve the welfare of those worst off.

$$\max_{x} \min_{i} \{u_i(x_i)\}$$
$$x \in S$$

Rawlsian Difference Principle

- The root idea is that when I make a decision for myself, I make a decision for **anyone** in similar circumstances.
    - It doesn’t matter who I am. (universality of reason)

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- Social contract argument
    - I make decisions (formulate a social contract) in an **original position**, behind a **veil of ignorance** as to who I am.
    - I must find the decision acceptable **after** I learn who I am.
    - I cannot rationally assent to a policy that puts me on the bottom, unless I would have been even **worse off** under alternative policies.
    - So the policy must **maximize** the welfare of the **worst off**.

Rawlsian Difference Principle

- Rawls intended the principle for the design of **social institutions**.
    - Not necessarily for other decisions.
    - Yet it is not unreasonable for resource allocation in general.
    - See J. Rawls, *A Theory of Justice*, 1971

Rawlsian Difference Principle

- The difference rule can be refined with a **leximax** principle**.**
  - If applied recursively.

- **Leximax (lexicographic maximum) principle**:
  - Maximize welfare of least advantaged class…
  - then next-to-least advantaged class…
  - and so forth.

Rawlsian Difference Principle

- There is no *practical* math programming model for leximax.

$$\text{leximax } \{u_1(x_1),\ldots,u_n(x_n)\}$$
$$x \in S$$

  - But see W. Ogryczak & T. Sliwinski, *ICCSA 2006.*

Rawlsian Difference Principle

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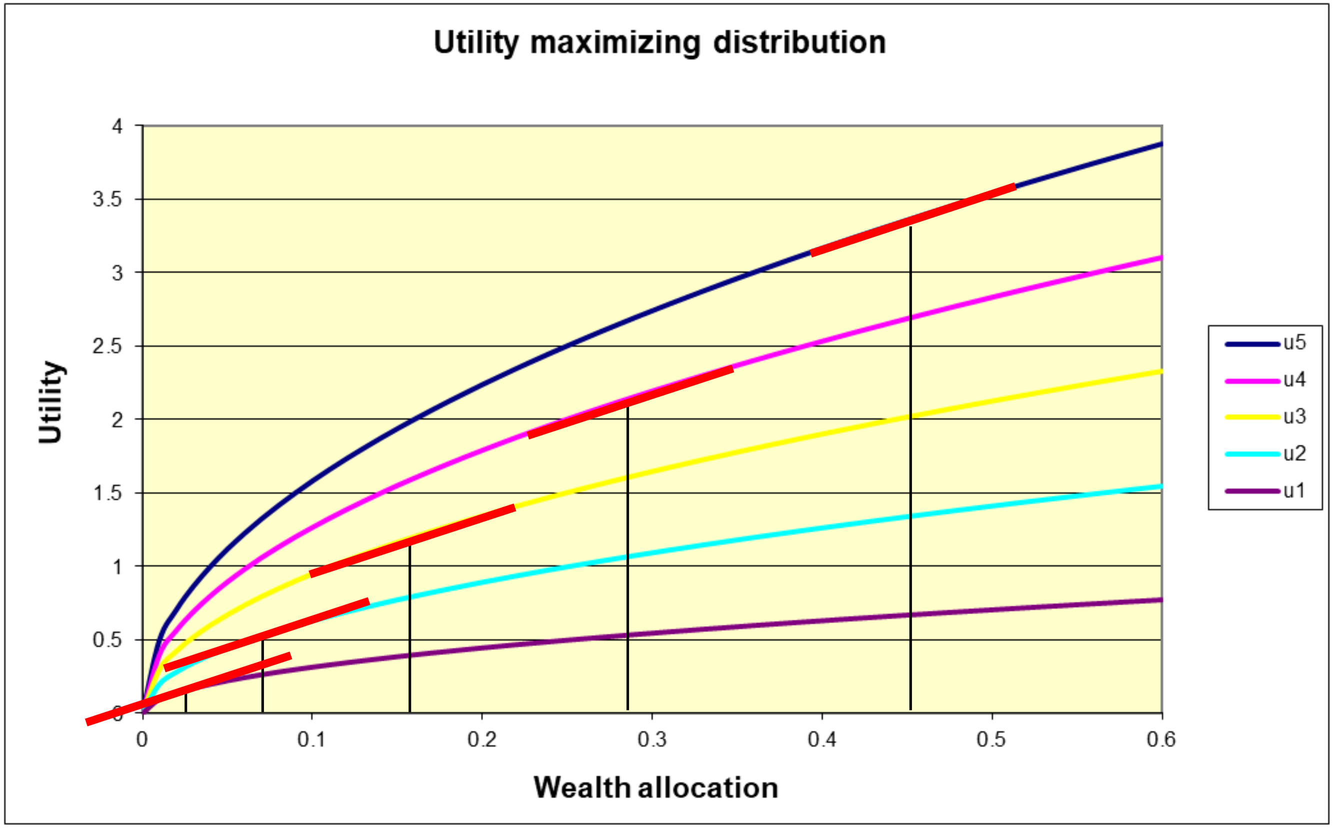
- We can solve the problem sequentially (pre-emptive goal programming).
  - Solve the maximin problem.
  - Fix the smallest u_i to its maximum value.
  - Solve the maximin problem over remaining u_i's.
  - Continue to u_n.

Rawlsian Difference Principle

- The Difference and Leximax Principles need not result in equality.
  - Consider the example presented earlier…

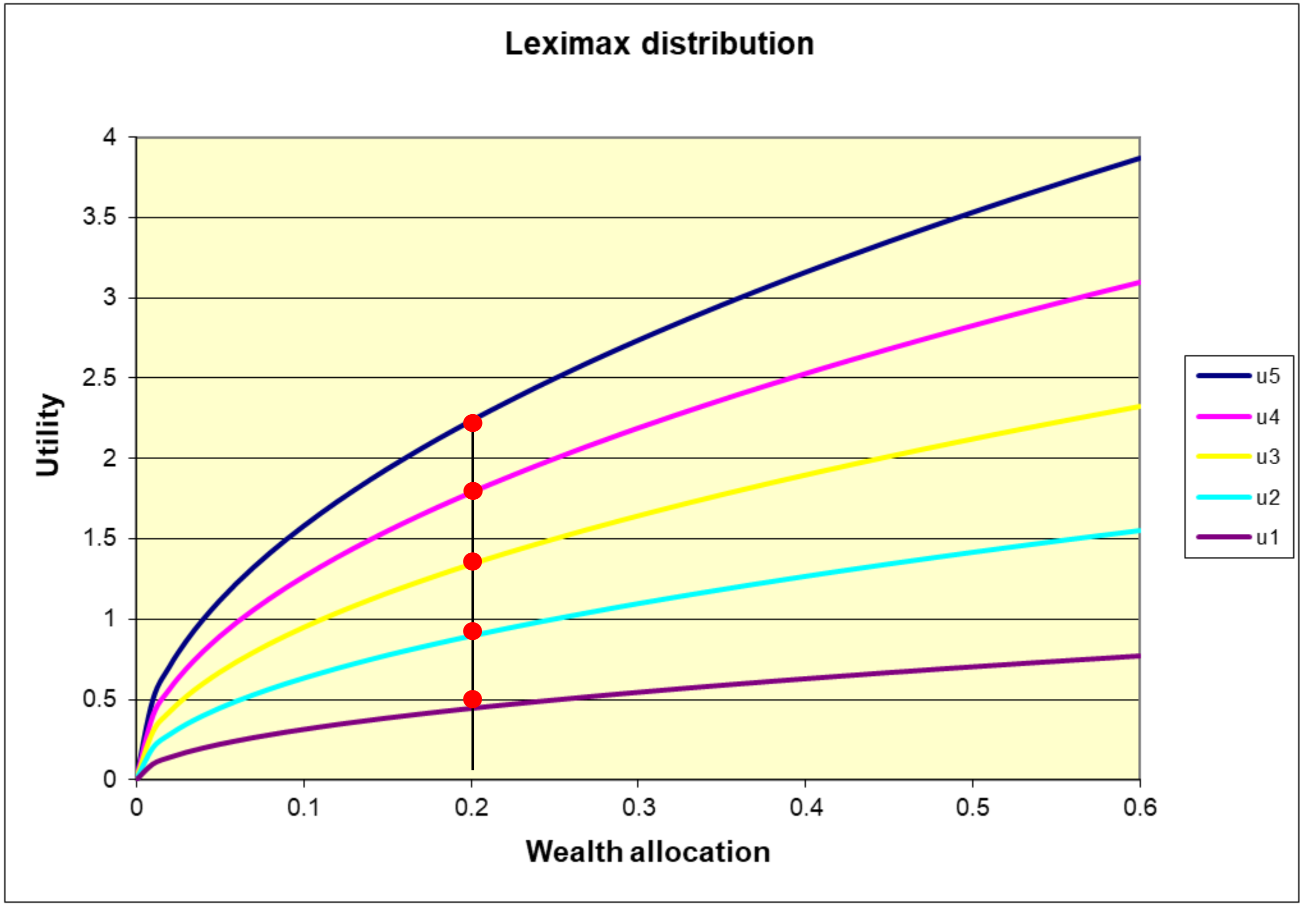
Rawlsian Difference Principle

Utilitarian distribution



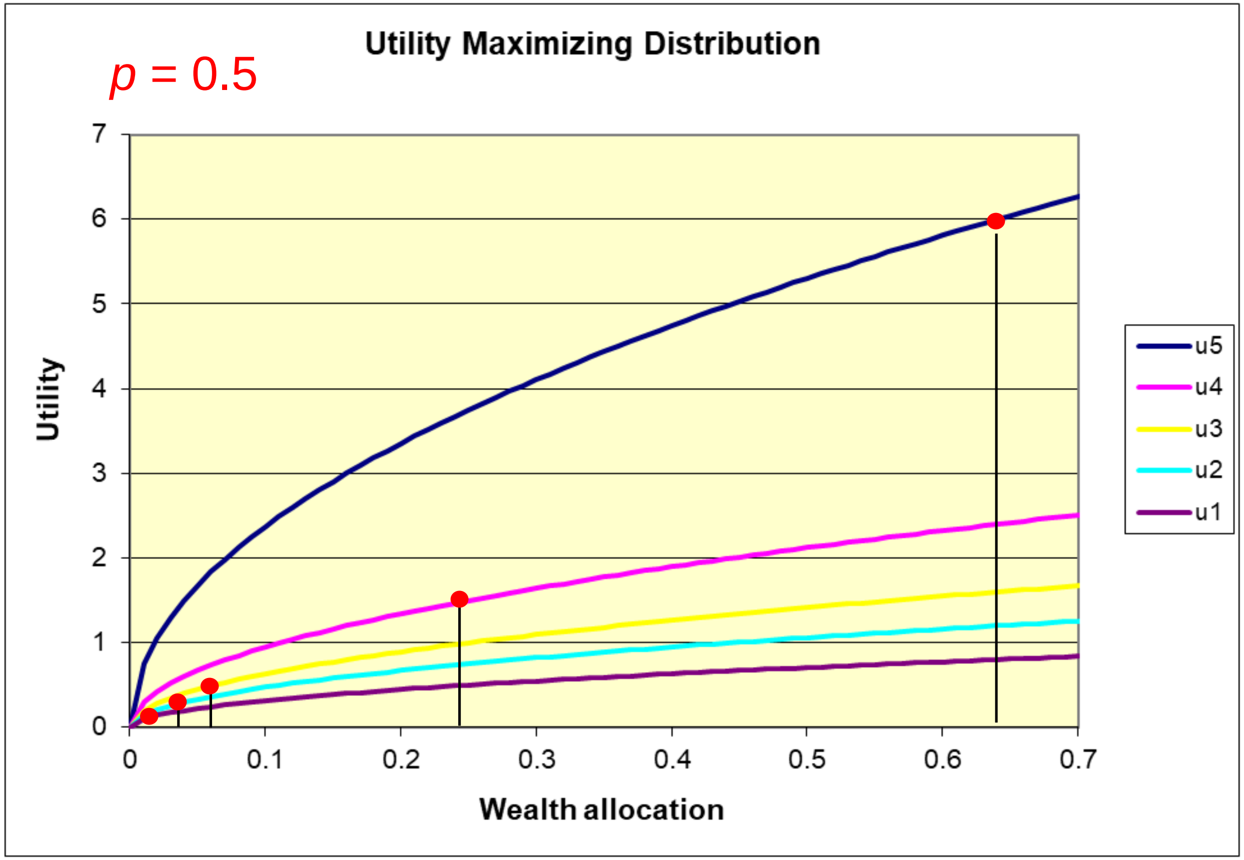
Rawlsian Difference Principle

Here, leximax principle results in equality



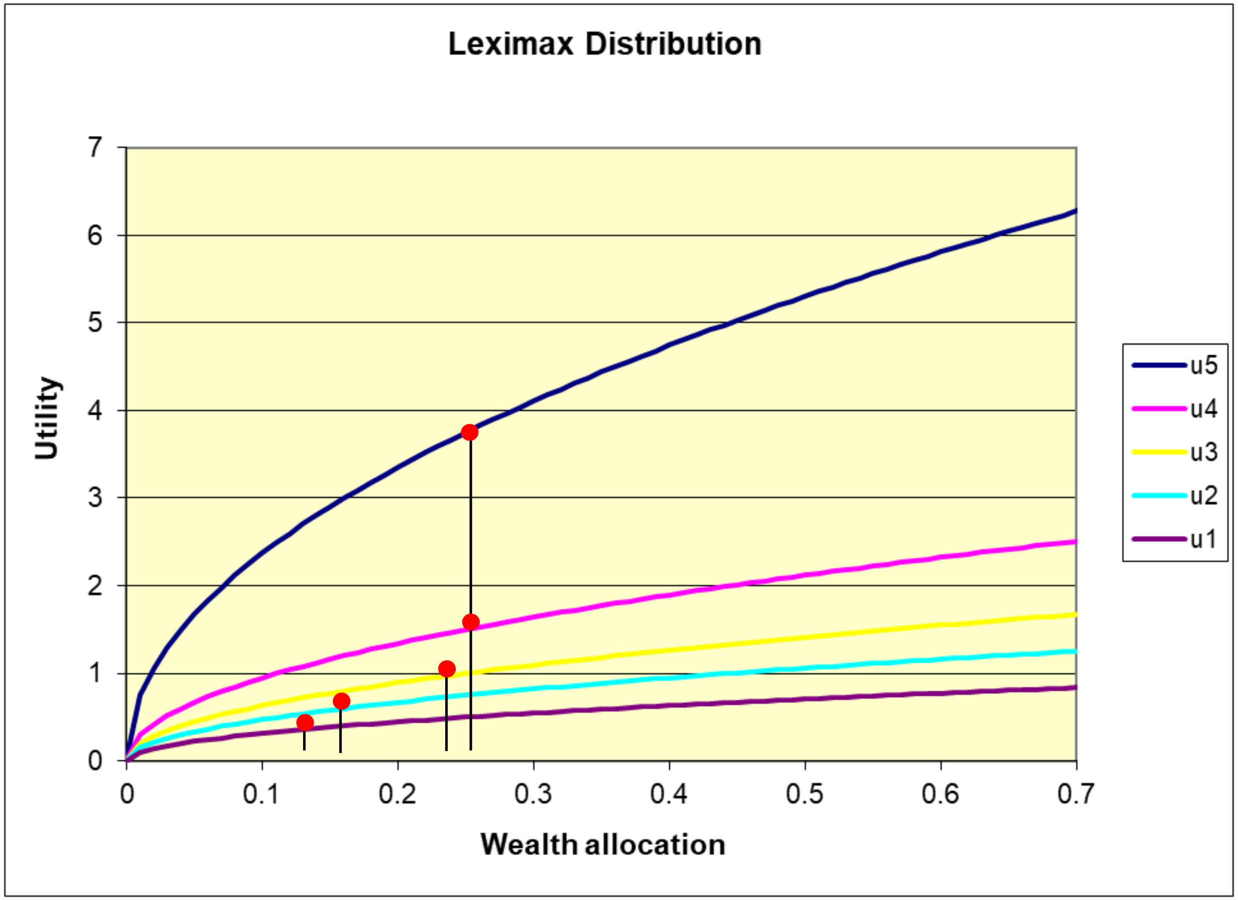
Utilitarianism

But consider this distribution…



Utilitarianism

Leximax doesn't result in equality



Axiomatics

- The economics literature derives social welfare functions from axioms of rational choice.
  - The social welfare function depends on degree of **interpersonal comparability** of utilities.
  - Arrow's impossibility theorem was the first result, but there are many others.
- **Social welfare function**
  - A function $f(u_1,\ldots,u_n)$ of individual utilities.
  - An optimization model can find a distribution of utility that maximizes social welfare.

Axiomatics

- The economics literature derives social welfare functions from axioms of rational choice.
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- **Social welfare function**
  - A function $f\,(u_1,\ldots,u_n)$ of individual utilities.
  - An optimization model can find a distribution of utility that maximizes social welfare.
- **Problem**
  - The SWF that results is little more than a restatement of the interpersonal comparability assumption.

Interpersonal Comparability

- Social Preferences
  - Let $u = (u_1,\ldots,u_n)$ be the vector of utilities allocated to individuals.
  - A social welfare function ranks distributions:
    u is preferable to u' if $f(u) > f(u')$.
- Invariance transformations.
  - These are transformations ϕ of utility vectors under which the ranking of distributions does not change.
  - Each $\phi = (\phi_1,\ldots,\phi_n)$, where ϕ_i is a transformation of individual utility u_i.

Interpersonal Comparability

- Ordinal noncomparability.
  - Any $\phi = (\phi_1,\ldots,\phi_n)$ with strictly increasing ϕ_is is an invariance transformation.
- Ordinal level comparability.
  - Any $\phi = (\phi_1,\ldots,\phi_n)$ with strictly increasing and identical ϕ_is is an invariance transformation.

Interpersonal Comparability

- Cardinal nonncomparability.
  - Any $\phi = (\phi_1,\ldots,\phi_n)$ with $\phi_i(u_i) = \alpha_i + \beta_i u_i$ and $\beta_i > 0$ is an invariance transformation.
- Cardinal unit comparability.
  - Any $\phi = (\phi_1,\ldots,\phi_n)$ with $\phi_i(u_i) = \alpha_i + \beta u_i$ and $\beta > 0$ is an invariance transformation.
- Cardinal ratio scale comparability
  - Any $\phi = (\phi_1,\ldots,\phi_n)$ with $\phi_i(u_i) = \beta u_i$ and $\beta > 0$ is an invariance transformation.

Axioms

- Anonymity
  - Social preferences are the same if indices of u_is are permuted.
- Strict pareto
  - If $u > u'$, then u is preferred to u'.
- Independence of irrelevant alternatives
  - The preference of u over u' depends only on u and u' and not on what other utility vectors are possible.
- Separability of unconcerned individuals
  - Individuals i for which $u_i = u_i'$ don't affect the ranking of u and u'.

Axiomatics

Theorem

Given **ordinal level comparability**, any social welfare function *f* that satisfies the axioms is lexicographically increasing or lexicographically decreasing. So we get a **leximax** or **leximin** objective.

Theorem

Given **cardinal unit comparability**, any social welfare function *f* that satisfies the axioms has the form $f(u) = \Sigma_i \, a_i u_i$ for $a_i \geq 0$. Se we get a **utilitarian** objective.

Axiomatics

Theorem

Given **cardinal noncomparability**, any social welfare function f that satisfies the axioms (except anonimity and separability) has the form $f(u) = u_i$ for some fixed i. So individual i is a **dictator**.

Theorem

Given **cardinal ratio scale comparability**, any social welfare function f that satisfies the axioms has the form $f(u) = \Sigma_i u_i^p/p$. Se we get the utility function used in the example.

Measures of Inequality

- Assume we wish to **minimize inequality**.
  - We will survey several measures of inequality.
  - They have different strengths and weaknesses.
  - Minimizing inequality may result in less total utility.

- **Pigou-Dalton** condition.
  - One criterion for evaluating an inequality measure.
  - If utility is transferred from one who is better off to one who is worse off, social welfare should increase.

Measures of Inequality

- Measures of Inequality
    - Relative range, max, min
    - Relative mean deviation
    - Variance, coefficient of variation
    - McLoone index
    - Gini coefficient
    - Atkinson index
    - Hoover index
    - Theil index

Relative Range

$$\frac{u_{\max} - u_{\min}}{\bar{u}}$$

where $u_{\max} = \max_i \{u_i\}$ $\quad u_{\min} = \min_i \{u_i\}$ $\quad \bar{u} = (1/n)\sum_i u_i$

Rationale:

- Perceived inequality is relative to the best off.
- A distribution should be judged by the position of the worst-off.
- Therefore, minimize gap between top and bottom.

Problems:

- Ignores distribution between extremes.
- Violates Pigou-Dalton condition

Relative Range

$$\frac{u_{\max} - u_{\min}}{\bar{u}}$$

This is a **fractional linear programming** problem.

Use Charnes-Cooper transformation to an LP. In general,

$$\begin{array}{lcl}
\min \dfrac{cx + c_0}{dx + d_0} & & \min cx' + c_0 z \\
Ax \geq b & \text{becomes} & Ax' \geq bz \\
x \geq 0 & & dx' + d_0 z = 1 \\
 & & x', z \geq 0
\end{array}$$

after change of variable $x = x'/z$ and fixing denominator to 1.

Relative Range

$$\frac{u_{\max} - u_{\min}}{\bar{u}}$$

Fractional LP model:

$$\min \frac{u_{\max} - u_{\min}}{(1/n)\sum_i u_i}$$

$$u_{\max} \geq u_i,\ u_{\min} \leq u_i,\ \text{all } i$$

$$u_i = a_i x_i,\ 0 \leq x_i \leq b_i,\ \text{all } i,\quad \sum_i x_i = B$$

LP model:

$$\min u_{\max} - u_{\min}$$

$$u_{\max} \geq u_i',\ u_{\min} \leq u_i',\ \text{all } i$$

$$u_i' = a_i x_i',\ 0 \leq x_i' \leq b_i z,\ \text{all } i,\quad \sum_i x_i' = Bz$$

$$(1/n)\sum_i u_i' = 1$$

Relative Max

$$\frac{u_{\max}}{\bar{u}}$$

Rationale:

- Perceived inequality is relative to the best off.
- Possible application to salary levels (typical vs. CEO)

Problems:

- Ignores distribution below the top.
- Violates Pigou-Dalton condition

Relative Max

$$\frac{u_{\max}}{\bar{u}}$$

Fractional LP model:

$$\min \frac{u_{\max}}{(1/n)\sum_i u_i}$$

$$u_{\max} \geq u_i,\ \text{all } i$$

$$u_i = a_i x_i,\ 0 \leq x_i \leq b_i,\ \text{all } i,\quad \sum_i x_i = B$$

LP model:

$$\min u_{\max}$$

$$u_{\max} \geq u_i' \ \text{all } i$$

$$u_i' = a_i x_i',\ 0 \leq x_i' \leq b_i z,\ \text{all } i,\quad \sum_i x_i' = Bz$$

$$(1/n)\sum_i u_i' = 1$$

Relative Min

$$\frac{u_{\min}}{\bar{u}}$$

Rationale:

- Measures adherence to Rawlsian Difference Principle.
- …relativized to mean

Problems:

- Ignores distribution above the bottom.
- Violates Pigou-Dalton condition

Relative Min

$$\frac{u_{\min}}{\bar{u}}$$

Fractional LP model:

$$\max \frac{u_{\min}}{(1/n)\sum_i u_i}$$

$$u_{\min} \le u_i, \text{ all } i$$

$$u_i = a_i x_i, \;\; 0 \le x_i \le b_i, \;\; \text{all } i, \quad \sum_i x_i = B$$

LP model:

$$\max u_{\min}$$

$$u_{\min} \ge u_i' \text{ all } i$$

$$u_i' = a_i x_i', \;\; 0 \le x_i' \le b_i z, \;\; \text{all } i, \quad \sum_i x_i' = Bz$$

$$(1/n)\sum_i u_i' = 1$$

Relative Mean Deviation

$$\frac{\sum_i \left| u_i - \bar{u} \right|}{\bar{u}}$$

Rationale:

- Perceived inequality is relative to average.
- Entire distribution should be measured.

Problems:

- Violates Pigou-Dalton condition
- Insensitive to transfers on the same side of the mean.
- Insensitive to placement of transfers from one side of the mean to the other.

Relative Mean Deviation

$$\frac{\sum_i \left| u_i - \bar{u} \right|}{\bar{u}}$$

Fractional LP model:

$$\max \frac{\sum_i (u_i^+ + u_i^-)}{\bar{u}}$$

$$u_i^+ \ge u_i - \bar{u},\ u_i^- \ge \bar{u} - u_i,\ \text{all } i$$

$$\bar{u} = (1/n)\sum_i u_i$$

$$u_i = a_i x_i,\ 0 \le x_i \le b_i,\ \text{all } i,\quad \sum_i x_i = B$$

LP model:

$$\max \sum_i (u_i^+ + u_i^-)$$

$$u_i^+ \ge u_i' - 1,\ u_i^- \le u_i' - 1,\ \text{all } i$$

$$(1/n)\sum_i u_i' = 1$$

$$u_i' = a_i x_i',\ 0 \le x_i' \le b_i z,\ \text{all } i,\quad \sum_i x_i' = Bz$$

Variance

$$(1/n)\sum_i (u_i - \bar{u})^2$$

Rationale:

- Weight each utility by its distance from the mean.
- Satisfies Pigou-Dalton condition.
- Sensitive to transfers on one side of the mean.
- Sensitive to placement of transfers from one side of the mean to the other.

Problems:

- Weighting is arbitrary?
- Variance depends on scaling of utility.

Variance

$$(1/n)\sum_i (u_i - \bar{u})^2$$

Convex nonlinear model: $\min\ (1/n)\sum_i (u_i - \bar{u})^2$

$$\bar{u} = (1/n)\sum_i u_i$$

$$u_i = a_i x_i,\ 0 \le x_i \le b_i,\ \text{all } i, \quad \sum_i x_i = B$$

Coefficient of Variation

$$\frac{\left((1/n)\sum_i (u_i - \bar{u})^2 \right)^{1/2}}{\bar{u}}$$

Rationale:

- Similar to variance.
- Invariant with respect to scaling of utilities.

Problems:

- When minimizing inequality, there is an incentive to reduce average utility.
- Should be minimized only for fixed total utility.

Coefficient of Variation

$$\frac{\left((1/n)\sum_i (u_i - \bar{u})^2\right)^{1/2}}{\bar{u}}$$

Again use change of variable $u = u'/z$ and fix denominator to 1.

$$\min \frac{\left((1/n)\sum_i (u_i - \bar{u})^2\right)^{1/2}}{\bar{u}}$$
$$Au \geq b$$
$$u \geq 0$$

becomes

$$\min \left((1/n)\sum_i (u_i' - 1)^2\right)^{1/2}$$
$$Au' \geq bz$$
$$(1/n)\sum_i u_i' = 1$$
$$u' \geq 0$$

Can drop exponent to make problem convex

Coefficient of Variation

$$\frac{\left((1/n)\sum_i (u_i - \bar{u})^2\right)^{1/2}}{\bar{u}}$$

Fractional nonlinear model:

$$\max \frac{\left((1/n)\sum_i (u_i - \bar{u})^2\right)^{1/2}}{\bar{u}}$$

$$\bar{u} = (1/n)\sum_i u_i$$

$$u_i = a_i x_i,\ 0 \le x_i \le b_i,\ \text{all } i,\quad \sum_i x_i = B$$

Convex nonlinear model:

$$\min (1/n)\sum_i (u_i' - 1)^2$$

$$(1/n)\sum_i u_i' = 1$$

$$u_i' = a_i x_i',\ 0 \le x_i' \le b_i z,\ \text{all } i,\quad \sum_i x_i' = Bz$$

McLoone Index

$$\frac{(1/2)\sum_{i:u_i<m} u_i}{\bar{u}}$$

Rationale:

- Ratio of average utility below median to overall average.
- No one wants to be “below average.”
- Pushes average up while pushing inequality down.

Problems:

- Violates Pigou-Dalton condition.
- Insensitive to upper half.

McLoone Index

$$\frac{(1/2)\sum_{i:u_i<m} u_i}{\bar{u}}$$

Fractional MILP model:

$$\max \frac{\sum_i v_i}{\sum_i u_i}$$

Defines median m

$$m - My_i \le u_i \le m + M(1 - y_i),\ \text{ all } i$$

Defines $v_i = u_i$ if u_i is below median

$$v_i \le u_i, v_i \le My_i,\ \text{ all } i$$

Half of utilities are below median

$$\sum_i y_i < n/2$$

$$u_i = a_i x_i,\ 0 \le x_i \le b_i,\ \text{all } i,\quad \sum_i x_i = B$$

Selects utilities below median

$$y_i \in \{0,1\},\ \text{ all } i$$

McLoone Index

$$\frac{(1/2)\sum_{i:u_i<m} u_i}{\bar{u}}$$

MILP model: $\max \sum_i v_i'$

$$m' - My_i \le u_i' \le m' + M(1 - y_i), \ \text{all } i$$

$$v_i' \le u_i', v_i' \le My_i, \ \text{all } i$$

$$\sum_i y_i < n/2$$

$$u_i' = a_i x_i', \ 0 \le x_i' \le b_i z, \ \text{all } i, \quad \sum_i x_i' = Bz$$

$$y_i \in \{0,1\}, \ \text{all } i$$

Gini Coefficient

$$\frac{(1/n^2)\sum_{i,j}\left|u_i - u_j\right|}{2\bar{u}}$$

Rationale:

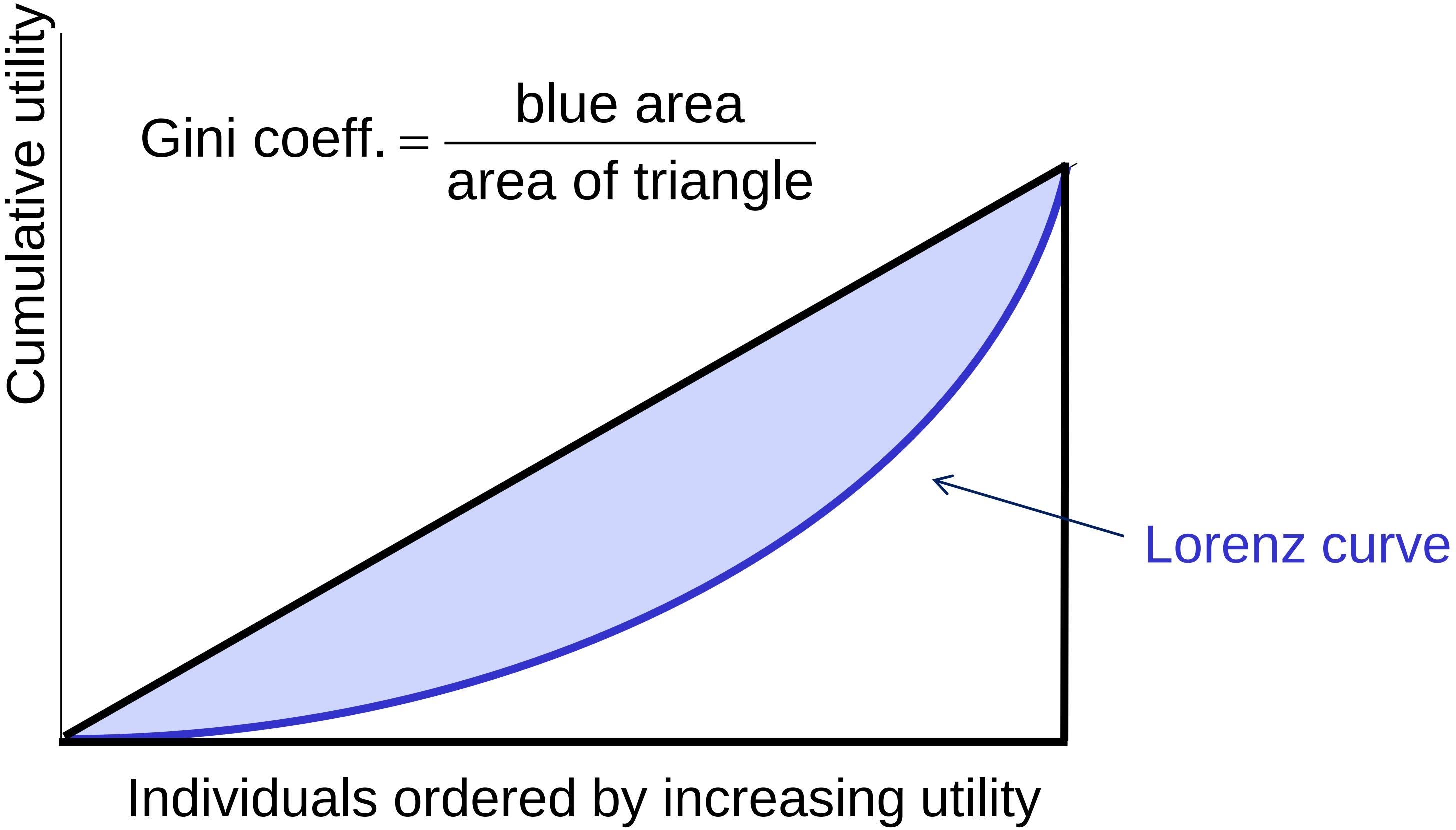
- Relative mean difference between all pairs.
- Takes all differences into account.
- Related to area above cumulative distribution (Lorenz curve).
- Satisfies Pigou-Dalton condition.

Problems:

- Insensitive to shape of Lorenz curve, for a given area.

Gini Coefficient

$$\frac{(1/n^2)\sum_{i,j}|u_i - u_j|}{2\bar{u}}$$



Gini Coefficient

$$\frac{(1/n^2)\sum_{i,j}\left|u_i - u_j\right|}{2\bar{u}}$$

Fractional LP model:

$$\max \frac{(1/2n^2)\sum_{ij}(u_{ij}^{+} + u_{ij}^{-})}{\bar{u}}$$

$$u_{ij}^{+} \geq u_i - u_j,\; u_{ij}^{-} \geq u_j - u_i,\; \text{all } i, j$$

$$\bar{u} = (1/n)\sum_i u_i$$

$$u_i = a_i x_i,\; 0 \leq x_i \leq b_i,\; \text{all } i, \quad \sum_i x_i = B$$

LP model:

$$\max\, (1/2n^2)\sum_{ij}(u_{ij}^{+} + u_{ij}^{-})$$

$$u_{ij}^{+} \geq u_i' - u_j',\; u_{ij}^{-} \geq u_j' - u_i',\; \text{all } i, j$$

$$(1/n)\sum_i u_i' = 1$$

$$u_i' = a_i x_i',\; 0 \leq x_i' \leq b_i z,\; \text{all } i, \quad \sum_i x_i' = Bz$$

Atkinson Index

$$1-\left(\boxed{(1/n)\sum_i \left(\frac{x_i}{\bar{x}}\right)^p}\right)^{1/p}$$

Rationale:

- Best seen as measuring inequality of **resources** x_i.
- Assumes allotment y of resources results in utility y^p
- This is average utility per individual.

Atkinson Index

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- Assumes allotment y of resources results in utility y^p
- This is average utility per individual.
- This is equal resource allotment to each individual that results in same total utility.

Atkinson Index

$$\boxed{1-\left((1/n)\sum_i\left(\frac{x_i}{\bar{x}}\right)^p\right)^{1/p}}$$

Rationale:

- Best seen as measuring inequality of **resources** x_i.
- Assumes allotment y of resources results in utility y^p
- This is average utility per individual.
- This is equal resource allotment to each individual that results in same total utility.
- This is additional resources per individual necessary to sustain inequality.

Atkinson Index

$$1-\left((1/n)\sum_i\left(\frac{x_i}{\overline{x}}\right)^p\right)^{1/p}$$

Rationale:

- p indicates “importance” of equality.
- Similar to L_p norm
- p = 1 means inequality has no importance
- p = 0 is Rawlsian (measures utility of worst-off individual).

Problems:

- Measures utility, not equality.
- Doesn’t evaluate distribution of utility, only of resources.
- p describes utility curve, not importance of equality.

Atkinson Index

$$1-\left((1/n)\sum_i\left(\frac{x_i}{\bar{x}}\right)^p\right)^{1/p}$$

To minimize index, solve fractional problem

$$\max \sum_i\left(\frac{x_i}{\bar{x}}\right)^p=\frac{\sum_i x_i^p}{\bar{x}^p}$$

$$Ax \ge b,\ \ x \ge 0$$

After change of variable $x_i = x_i'/z$, this becomes

$$\max \sum_i x_i'^p$$

$$(1/n)\sum_i x_i' = 1$$

$$Ax' \ge bz,\ \ x' \ge 0$$

Atkinson Index

$$1-\left((1/n)\sum_i \left(\frac{x_i}{\bar{x}}\right)^p\right)^{1/p}$$

Fractional nonlinear model:

$$\max \frac{\sum_i x_i^p}{\bar{x}^p}$$

$$\bar{x} = (1/n)\sum_i x_i$$

$$\sum_i x_i = B, \quad x \geq 0$$

Concave nonlinear model:

$$\max \sum_i x_i'^p$$

$$(1/n)\sum_i x_i' = 1$$

$$\sum_i x_i' = Bz, \quad x' \geq 0$$

Hoover Index

$$(1/2)\frac{\sum_i |u_i - \bar{u}|}{\sum_i u_i}$$

Rationale:

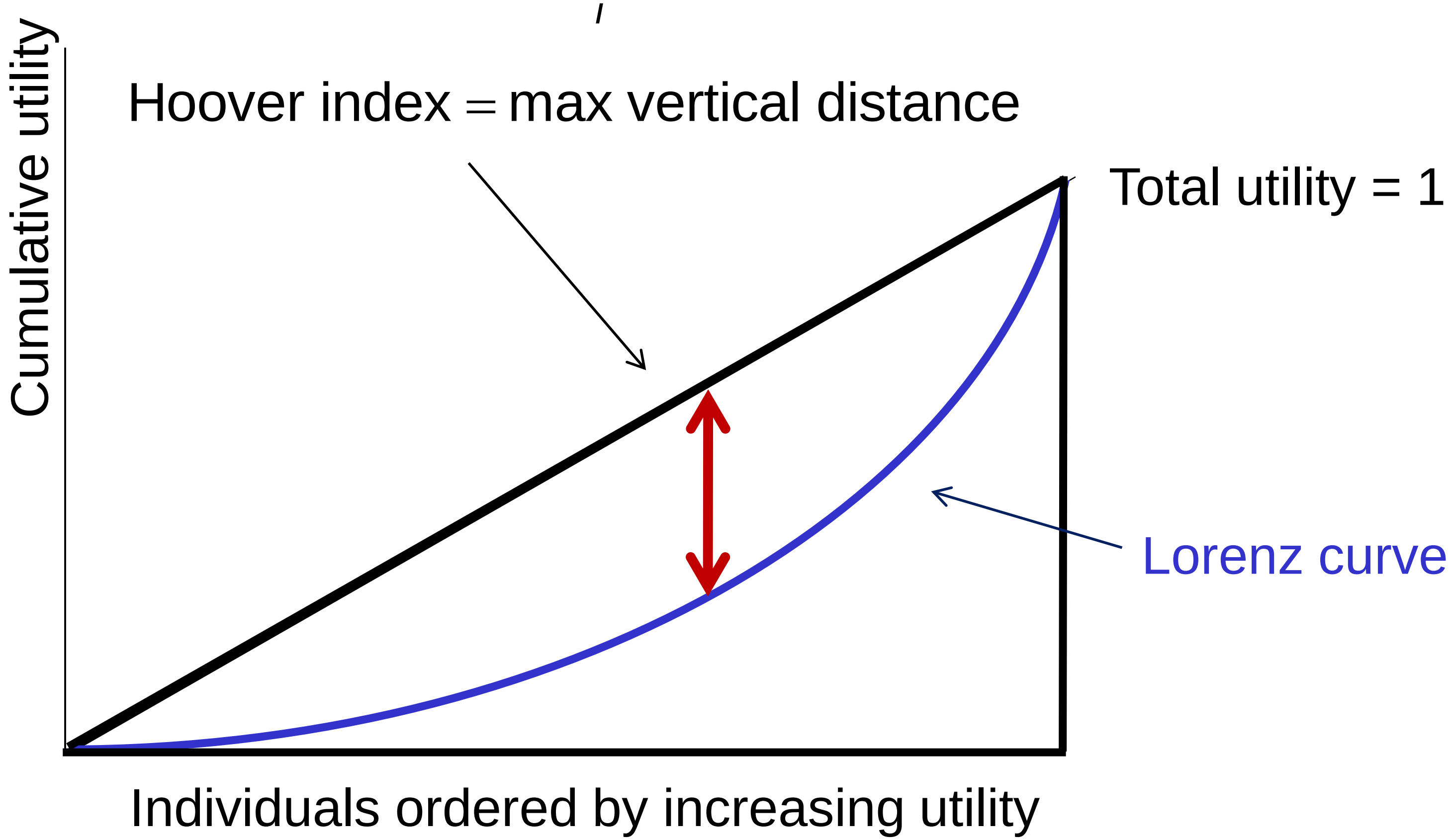
- Fraction of total utility that must be redistributed to achieve total equality.
- Proportional to maximum vertical distance between Lorenz curve and 45^{o} line.
- Originated in regional studies, population distribution, etc. (1930s).
- Easy to calculate.

Problems:

- Less informative than Gini coefficient?

Hoover Index

$$(1/2)\frac{\sum_i |u_i - \bar{u}|}{\sum_i u_i}$$



Theil Index

$$(1/n)\sum_i \left(\frac{u_i}{\bar{u}} \ln \frac{u_i}{\bar{u}} \right)$$

Rationale:

- One of a family of entropy measures of inequality.
- Index is zero for complete equality (maximum entropy)
- Measures nonrandomness of distribution.
- Described as stochastic version of Hoover index.

Problems:

- Motivation unclear.
- A. Sen doesn’t like it.

Theil Index

$$(1/n)\sum_i \left(\frac{u_i}{\bar{u}} \ln \frac{u_i}{\bar{u}} \right)$$

Nasty nonconvex model:

$$\min\, (1/n)\sum_i \left(\frac{u_i}{\bar{u}} \ln \frac{u_i}{\bar{u}} \right)$$

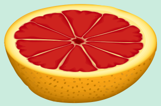
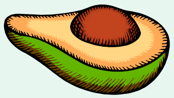
$$\bar{u} = (1/n)\sum_i u_i$$

$$u_i = a_i x_i,\ 0 \le x_i \le b_i,\ \text{all } i, \quad \sum_i x_i = B$$

A Fair Division Problem

- From Yaari and Bar-Hillel, 1983.
- **12 grapefruit** and **12 avocados** are to be divided between **Persons 1 and 2**.
- How to divide justly?

Utility provided by one fruit of each kind

	Person 1	Person 2
	100	50
	0	50

A Fair Division Problem

The optimization problem:

Social welfare function

$$\max \ f(u_1, u_2)$$

$$u_1 = 100x_{11}, \ u_2 = 50x_{12} + 50x_{22}$$

$$x_{i1} + x_{i2} = 12, \ i = 1,2$$

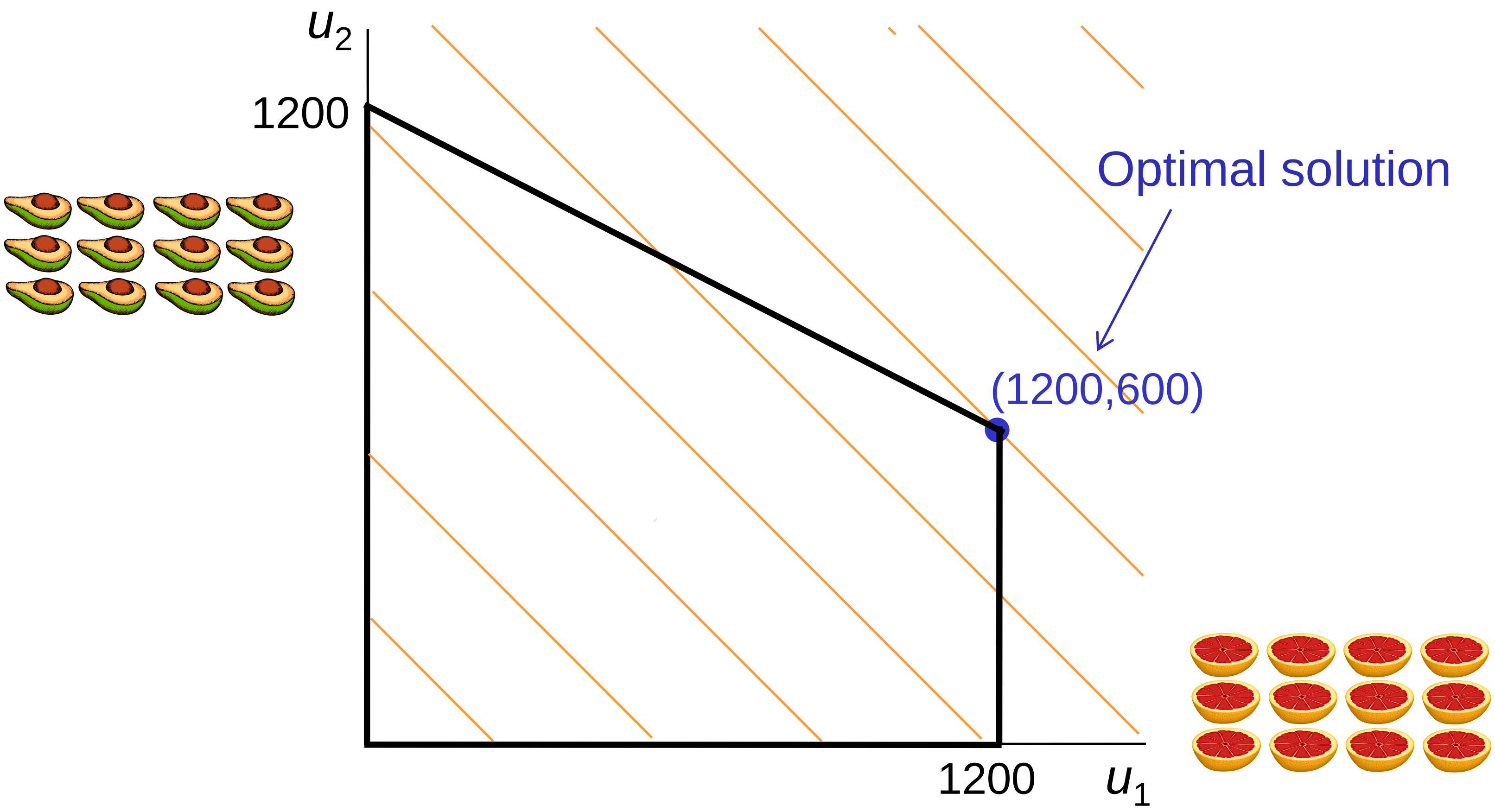
$$x_{ij} \geq 0, \ \text{all } i, j$$

where u_i = utility for person i

x_{ij} = allocation of fruit i (grapefruit, avocados) to person j

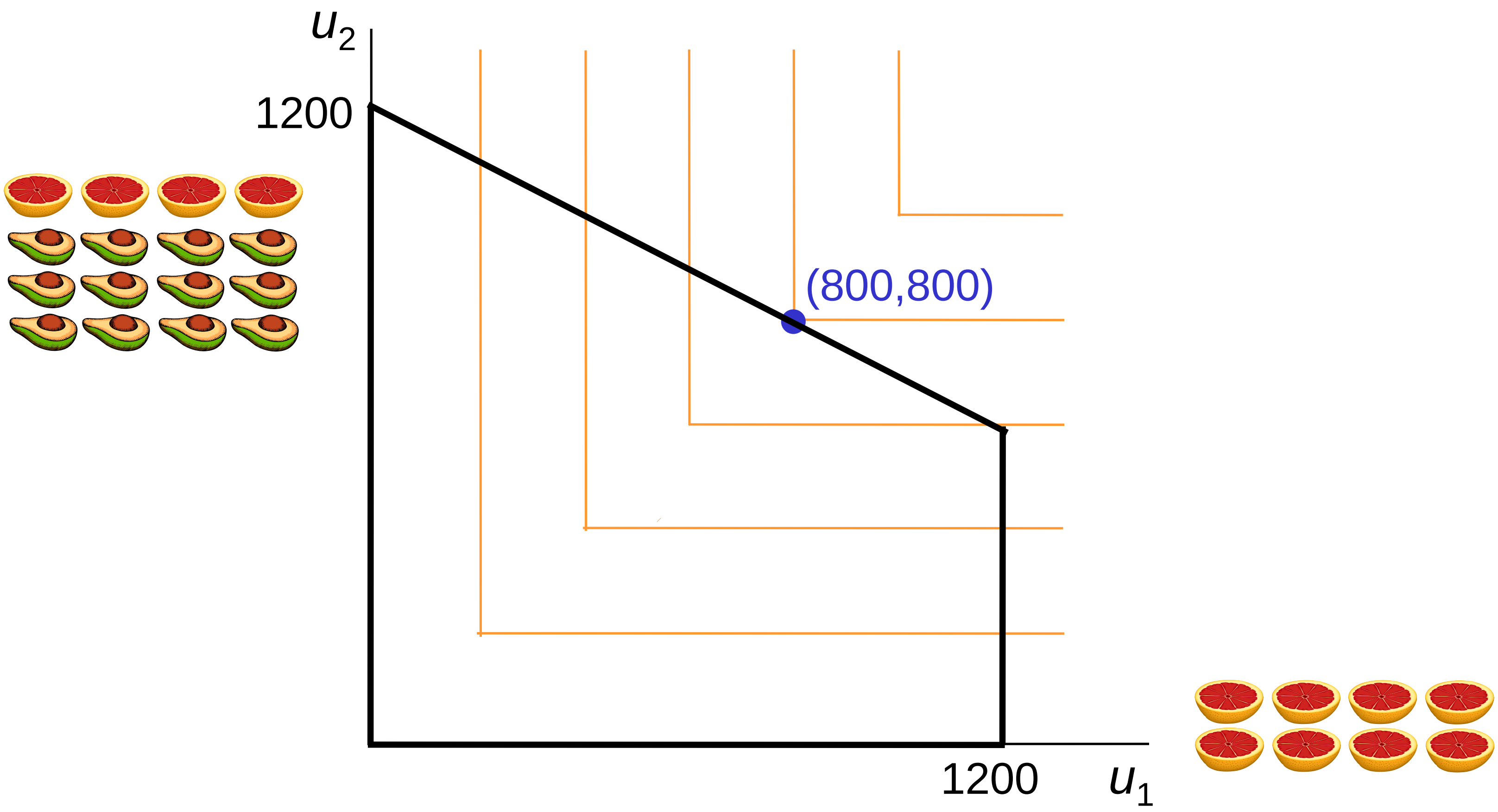
Utilitarian Solution

$$f(u_1,u_2) = u_1 + u_2$$



Rawlsian (maximin) solution

$$f(u_1,u_2) = \min\{u_1,u_2\}$$



Bargaining Solutions

- A **bargaining solution** is an equilibrium allocation in the sense that none of the parties wish to bargain further.

  - Because all parties are “satisfied” in some sense, the outcome may be viewed as “fair.”

  - Bargaining models have a **default** outcome, which is the result of a failure to reach agreement.

  - The default outcome can be seen as a **starting point**.

Bargaining Solutions

- Several proposals for the default outcome (starting point):
  - **Zero** for everyone. Useful when only the resources being allocated are relevant to fairness of allocation.
  - **Equal split**. Resources (not necessarily utilities) are divided equally. May be regarded as a “fair” **starting point**.
  - **Strongly pareto set**. Each party receives resources that can benefit no one else. Parties can always agree on this.

Nash Bargaining Solution

- Maximizes the **product of the gains** achieved by the bargainers, relative to the fallback position.
  - **Not** the same as **Nash equilibrium**.
  - Also known as **proportional fairness.**
  - Popular in engineering applications.
  - Used in **bandwidth allocation**, **traffic signal timing**, etc.

Nash Bargaining Solution

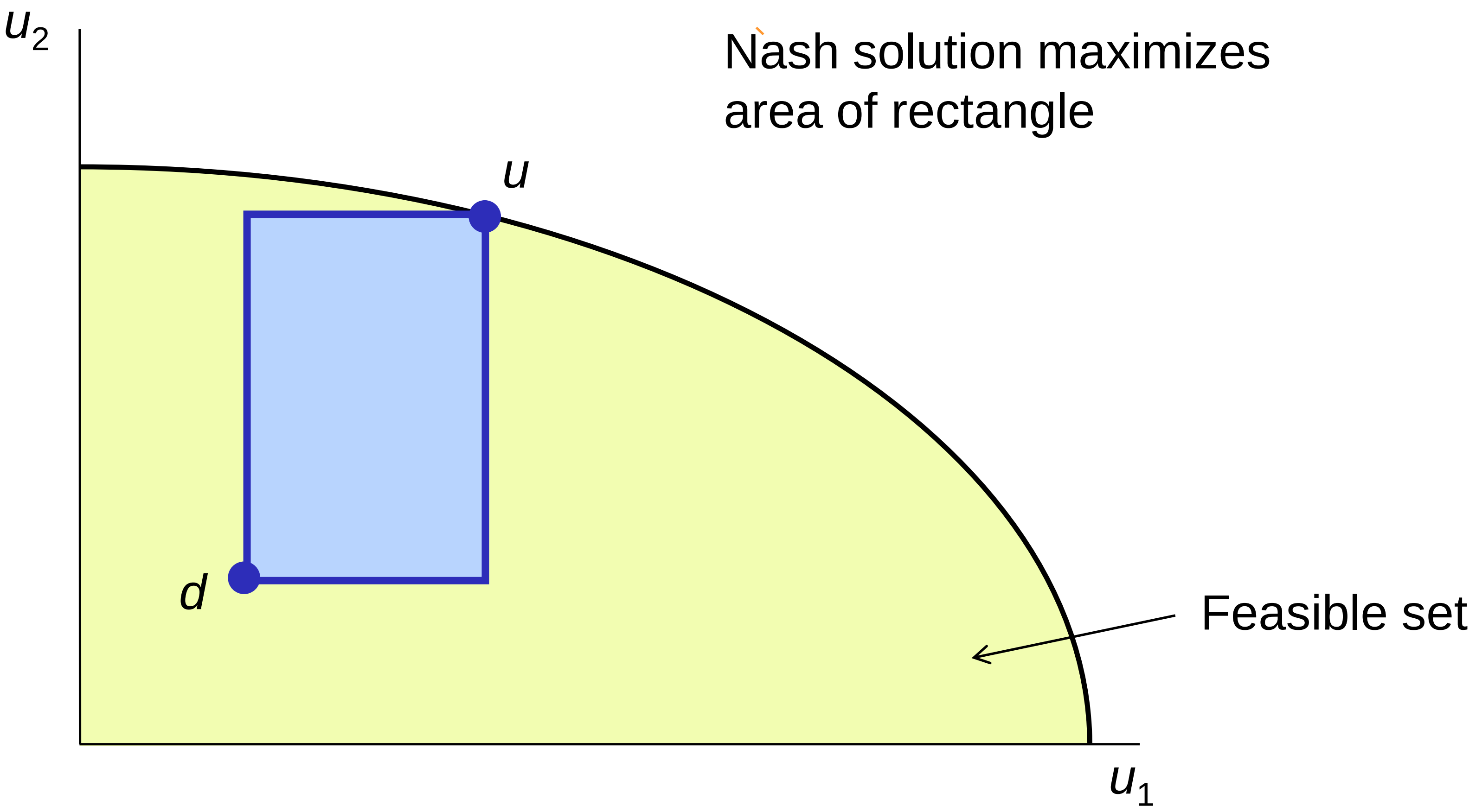
- The **Nash bargaining solution** maximizes the social welfare function

$$f(u) = \prod_i (u_i - d_i)$$

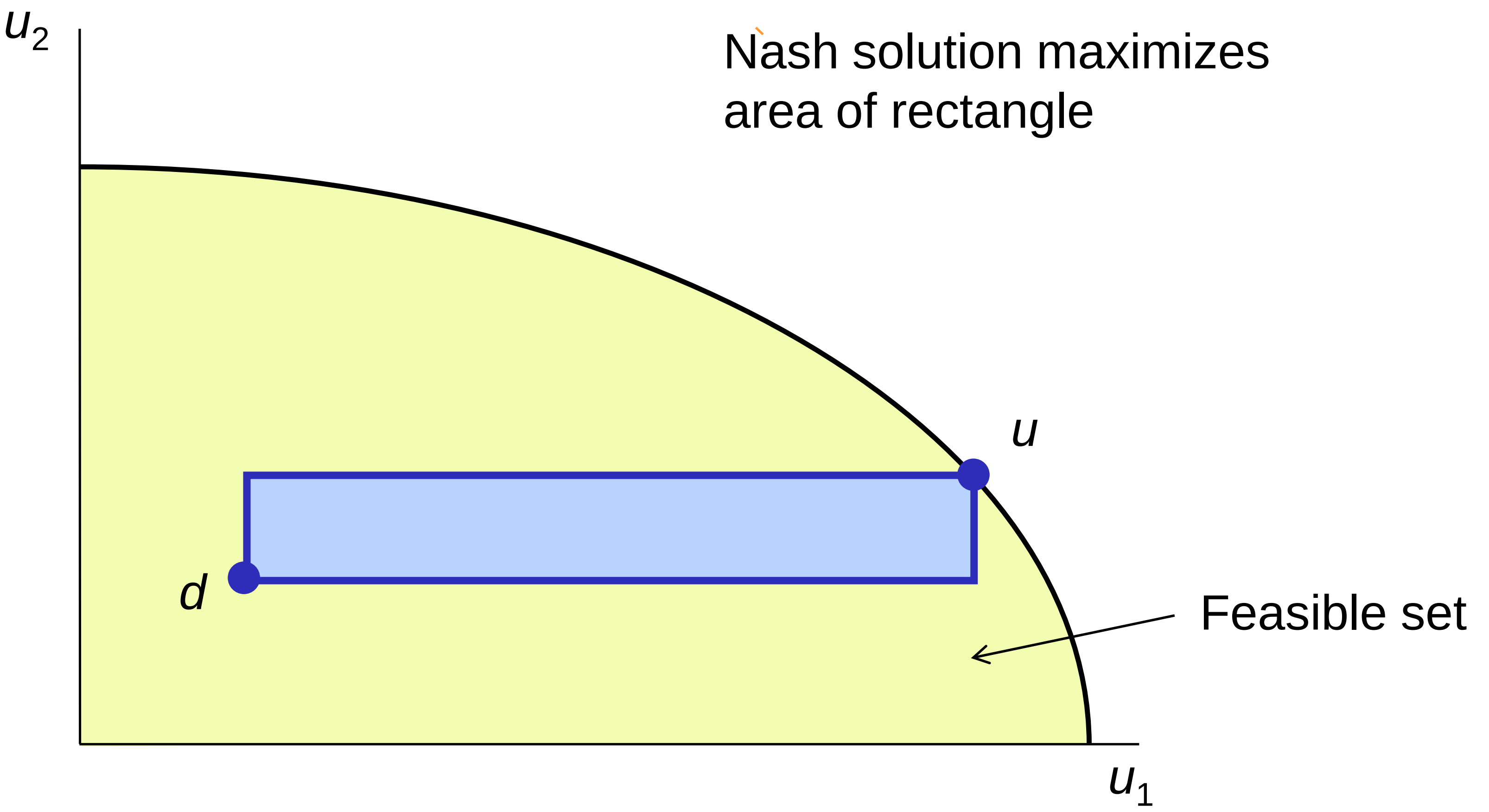
where *d* is the default outcome.

  - Assume feasible set is **convex**, so that Nash solution is unique (due to strict concavity of *f*).

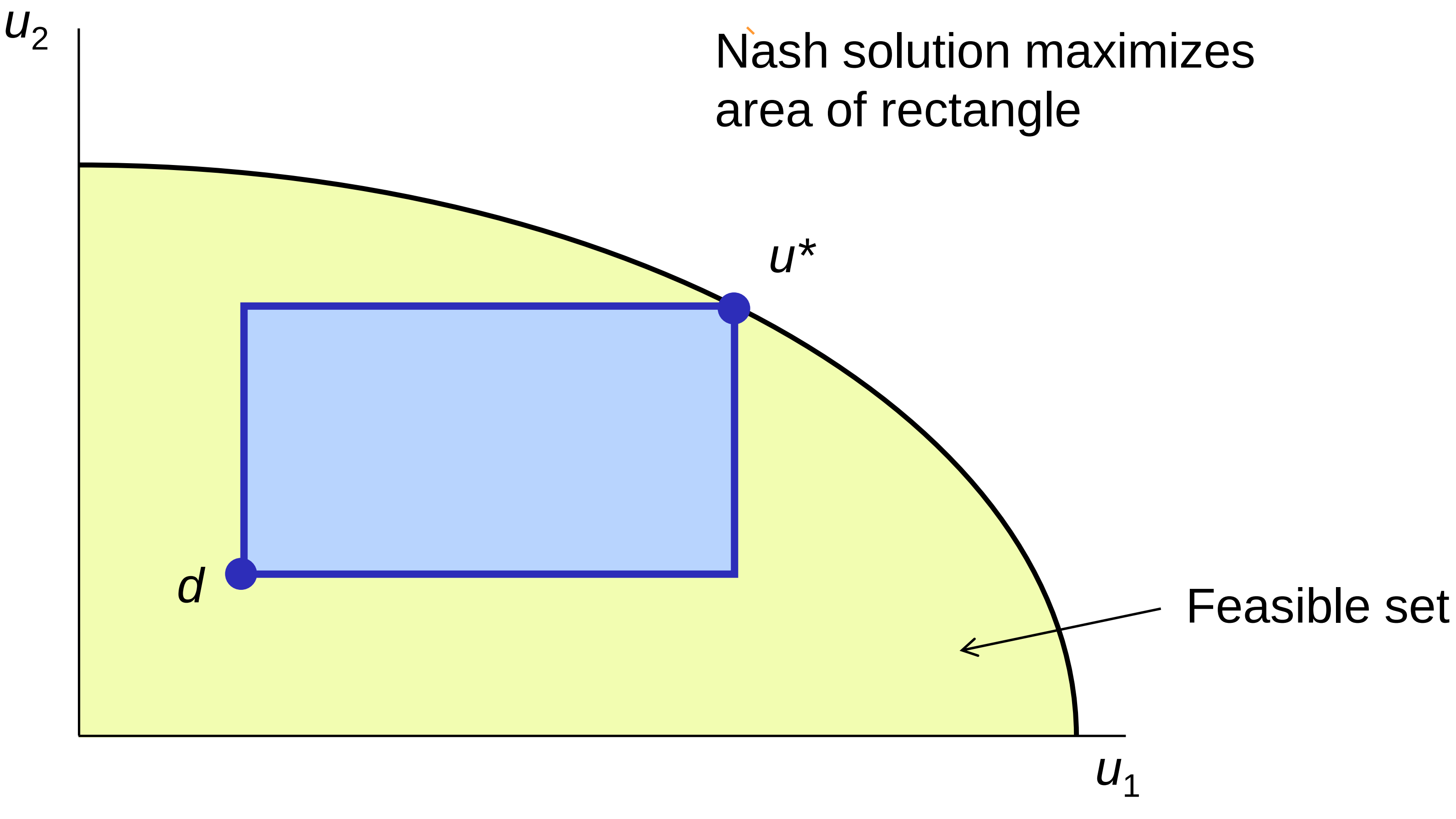
Nash Bargaining Solution



Nash Bargaining Solution



Nash Bargaining Solution



Nash Bargaining Solution

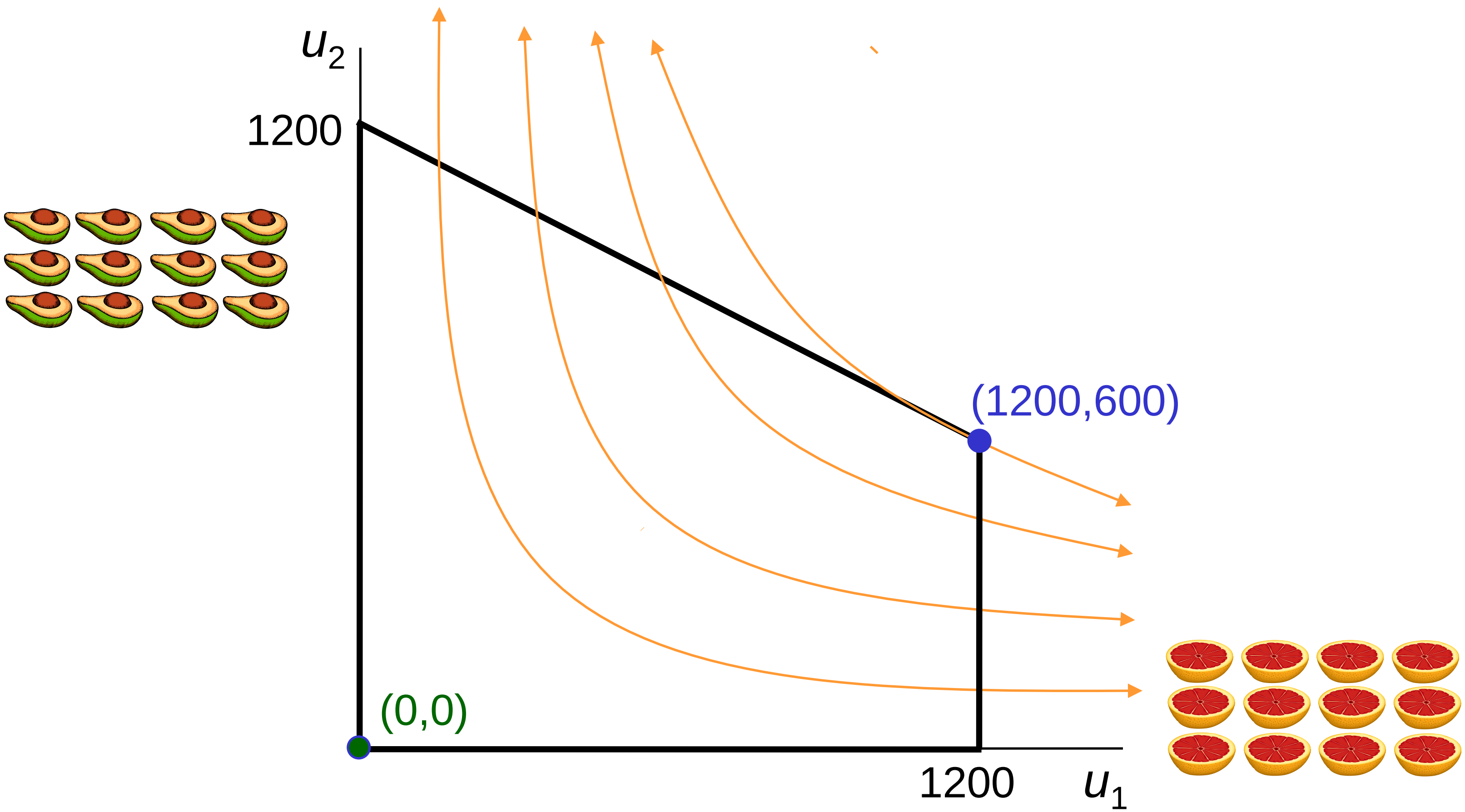
- The **optimization problem** has a concave objective function if we maximize log $f(u)$.

$$\max \log \prod_i (u_i - d_i) = \sum_i \log(u_i - d_i)$$
$$u \in S$$

- Problem is relatively easy if feasible set S is convex.

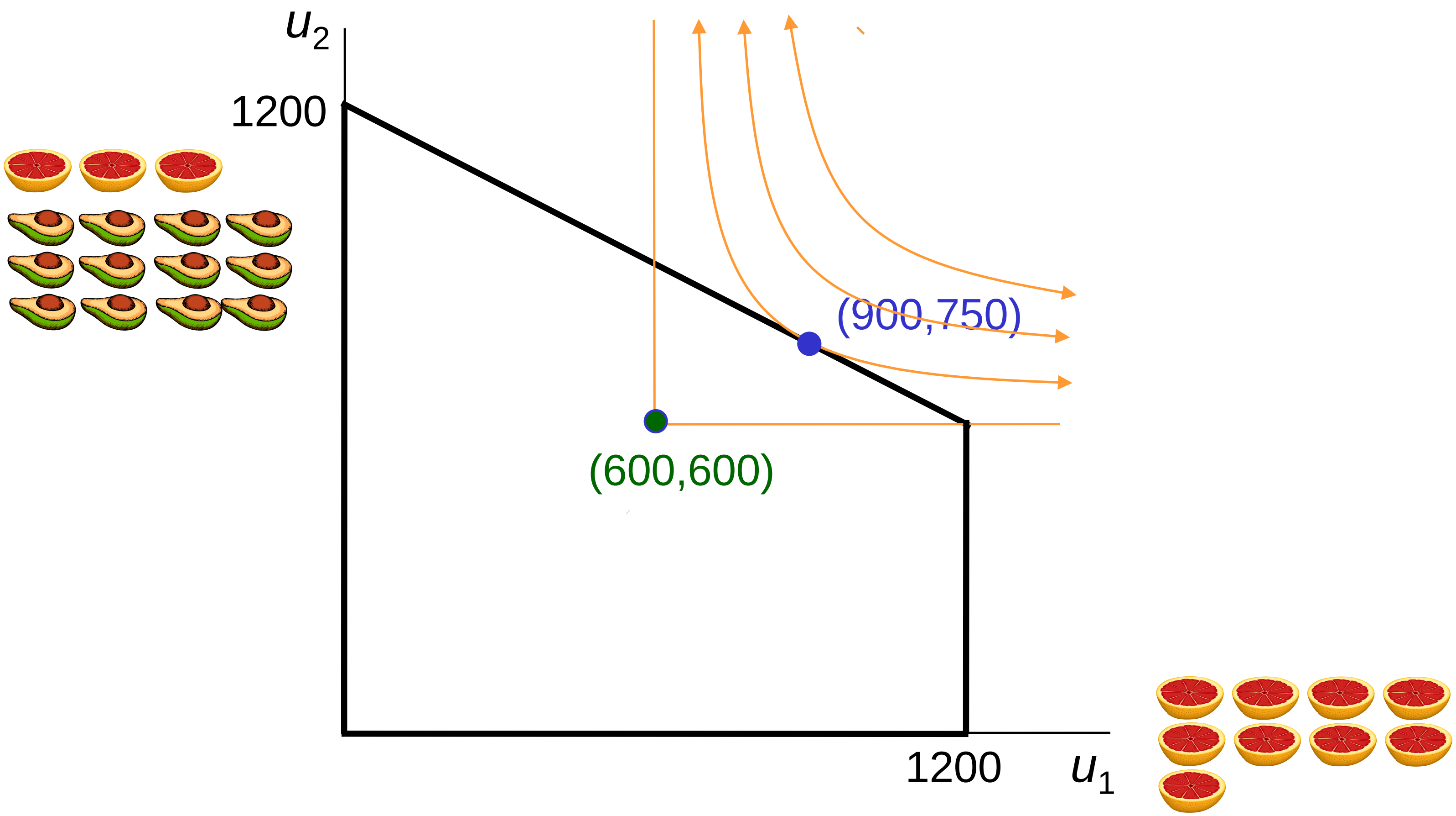
Nash Bargaining Solution

From Zero



Nash Bargaining Solution

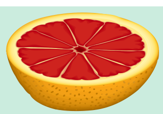
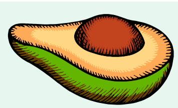
From Equality



Nash Bargaining Solution

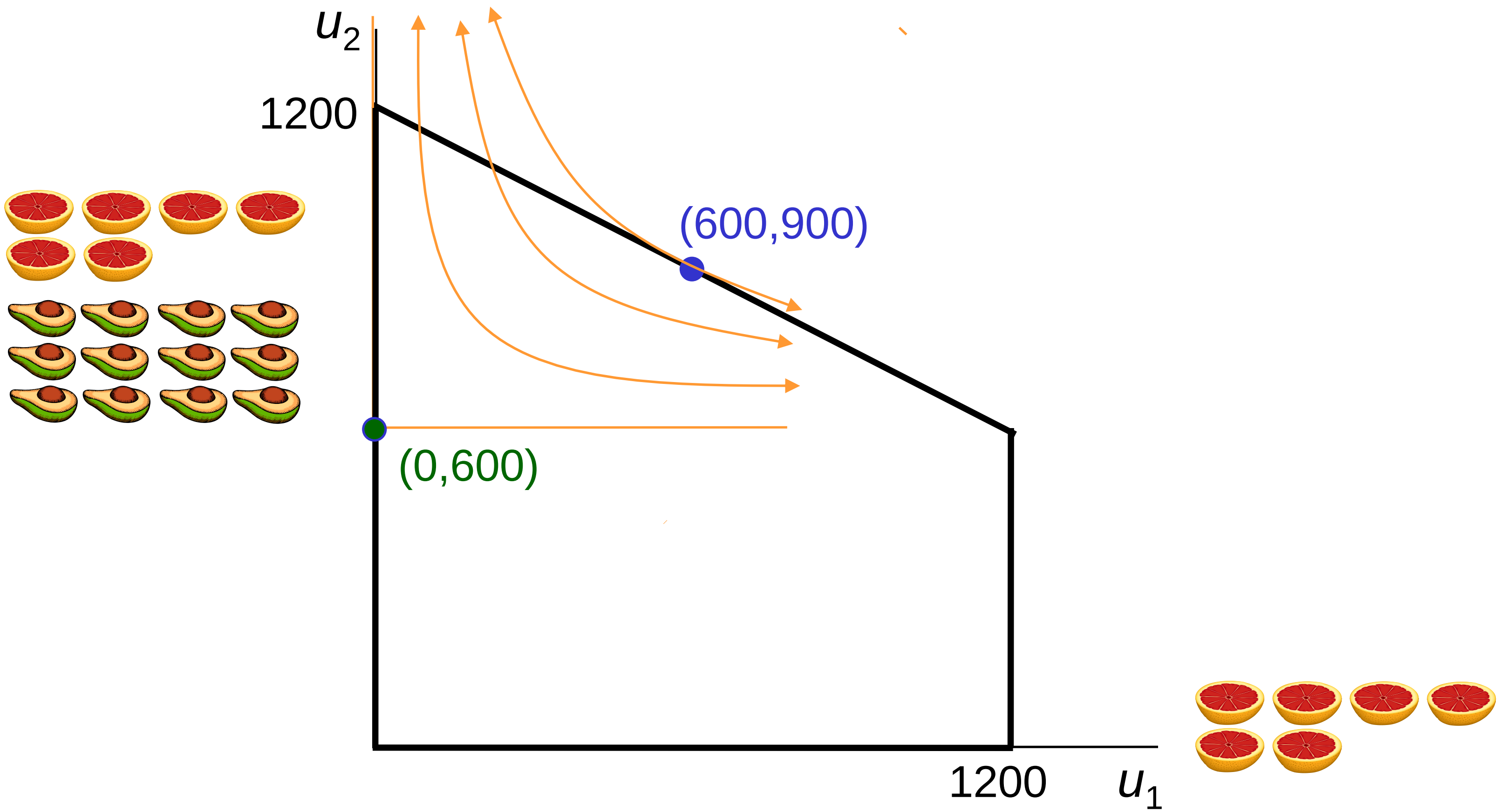
- **Strongly pareto set** gives Person 2 all 12 avocados.
  - Nothing for Person 1.
  - Results in utility $(u_1,u_2) = (0,600)$

Utility provided by one fruit of each kind

	Person 1	Person 2
	100	50
	0	50

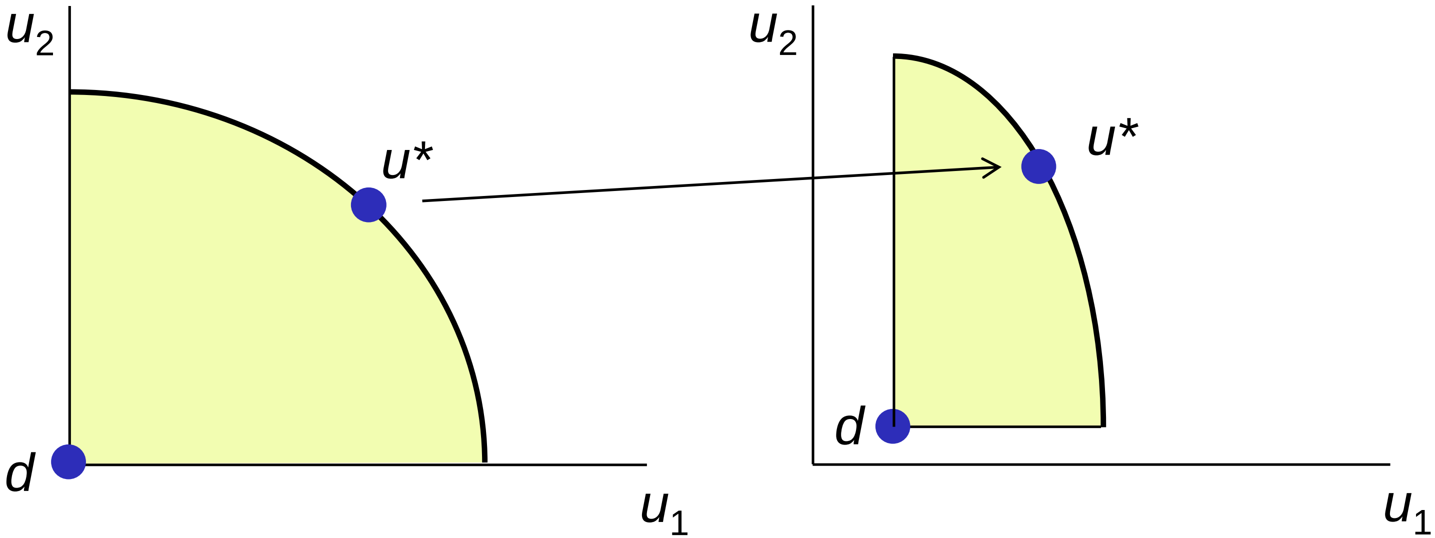
Nash Bargaining Solution

From Strongly Pareto Set



Axiomatic Justification

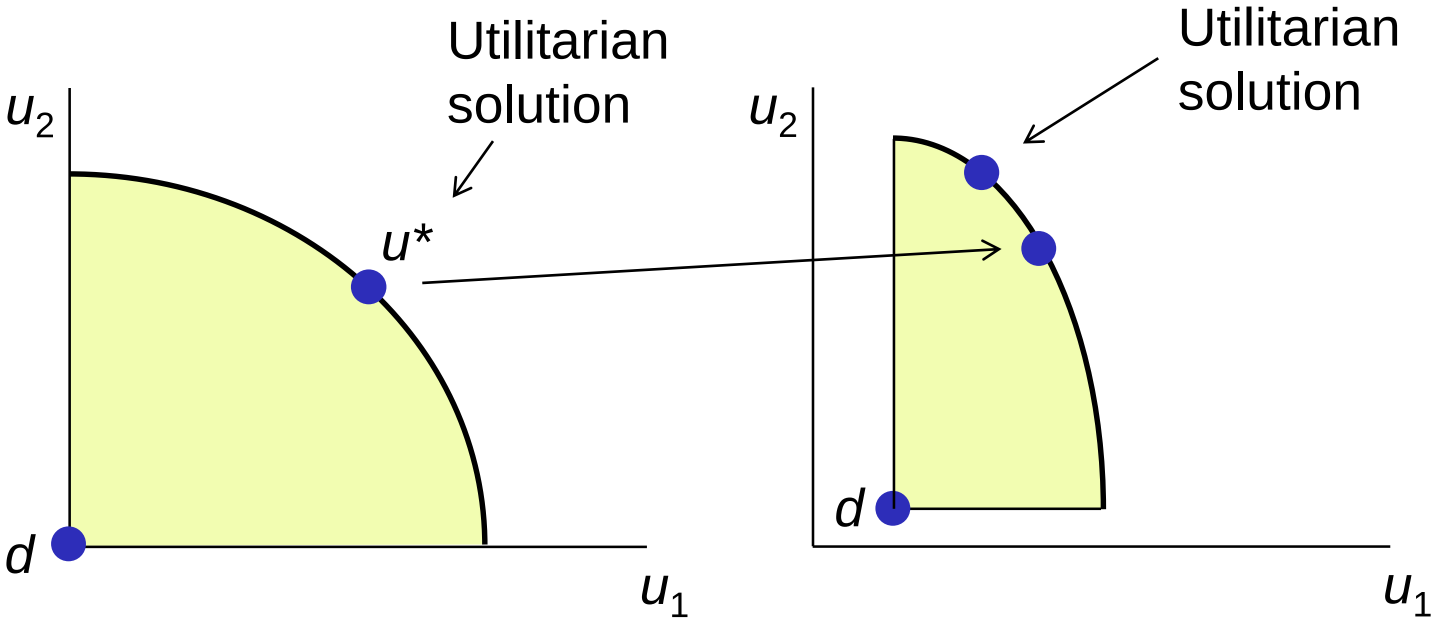
- **Axiom 1**. Invariance under translation and rescaling.
  - If we map $u_i \rightarrow a_i u_i + b_i$, $d_i \rightarrow a_i d_i + b_i$, then bargaining solution $u_i^* \rightarrow a_i u_i^* + b_i$.



This is **cardinal noncomparability**.

Axiomatic Justification

- **Axiom 1**. Invariance under translation and rescaling.
  - If we map $u_i \rightarrow a_i u_i + b_i$, $d_i \rightarrow a_i d_i + b_i$, then bargaining solution $u_i^* \rightarrow a_i u_i^* + b_i$.

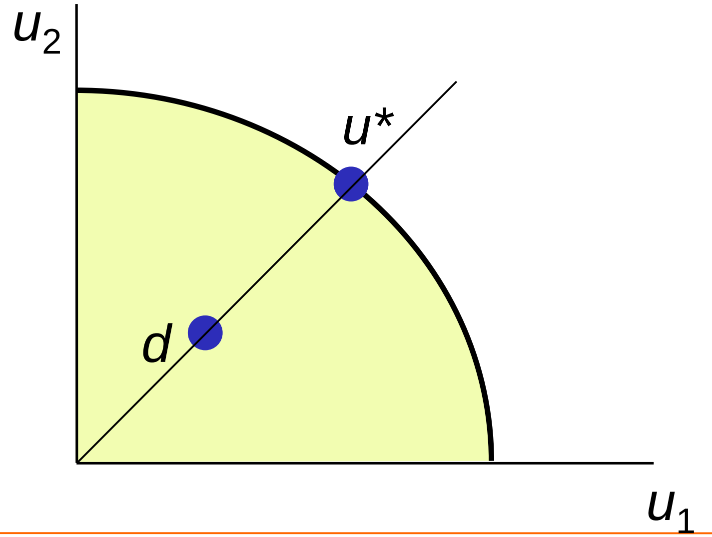


- **Strong assumption** – failed, e.g., by utilitarian welfare function

Axiomatic Justification

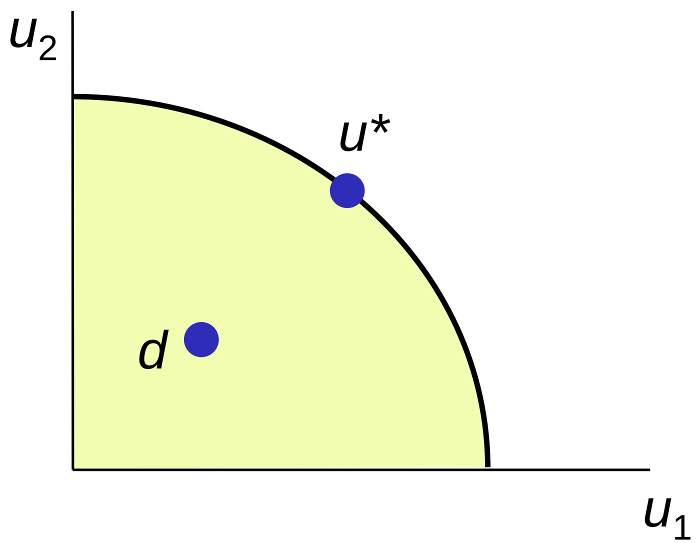
- **Axiom 2**. Pareto optimality.
  - Bargaining solution is pareto optimal.

- **Axiom 3.** Symmetry.
  - If all d_i's are equal and feasible set is symmetric, then all u_i*s are equal in bargaining solution.



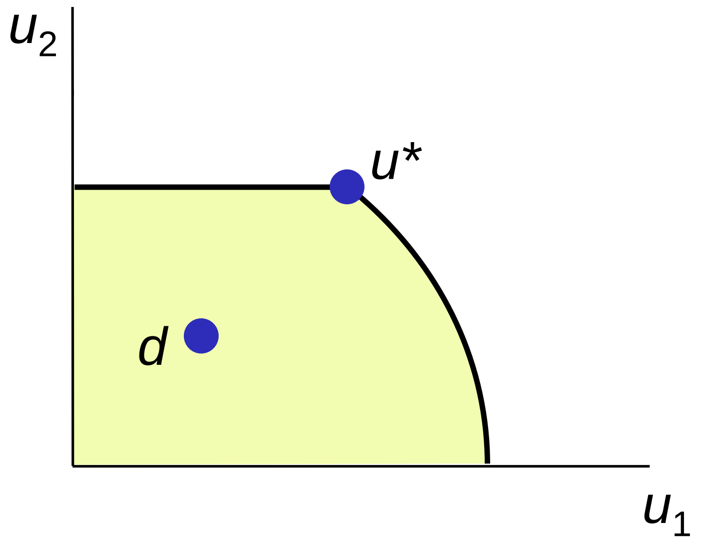
Axiomatic Justification

- **Axiom 4.** Independence of irrelevant alternatives.
  - Not the same as Arrow's axiom.
  - If u^* is a solution with respect to d…



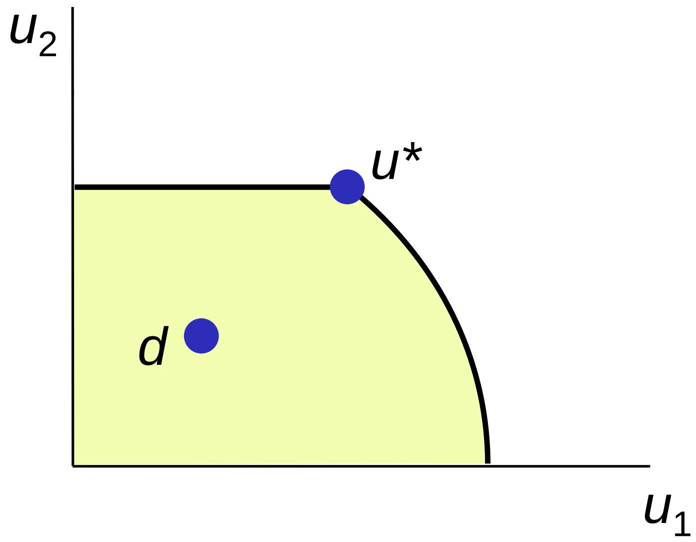
Axiomatic Justification

- **Axiom 4.** Independence of irrelevant alternatives.
  - Not the same as Arrow's axiom.
  - If u^* is a solution with respect to d, then it is a solution in a smaller feasible set that contains u^* and d.



Axiomatic Justification

- **Axiom 4.** Independence of irrelevant alternatives.
  - Not the same as Arrow's axiom.
  - If u^* is a solution with respect to d, then it is a solution in a smaller feasible set that contains u^* and d.
  - This basically says that the solution behaves like an **optimum**.



Axiomatic Justification

Theorem. Exactly one solution satisfies Axioms 1-4, namely the Nash bargaining solution.

Proof (2 dimensions).

First show that the Nash solution satisfies the axioms.

Axiom 1. Invariance under transformation. If

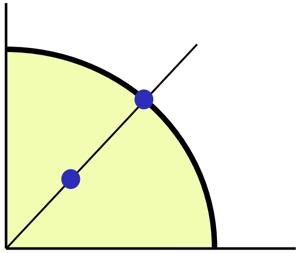
$$\prod_i (u_i^* - d_1) \geq \prod_i (u_i - d_1)$$

then

$$\prod_i \left((a_i u_i^* + b_i) - (a_i d_i + b_i)\right) \geq \prod_i \left((a_i u_i + b_i) - (a_i d_i + b_i)\right)$$

Axiomatic Justification

Axiom 2. Pareto optimality. Clear because social welfare function is strictly monotone increasing.



Axiom 3. Symmetry. Obvious.

Axiom 4. Independence of irrelevant alternatives. Follows from the fact that u^* is an optimum.

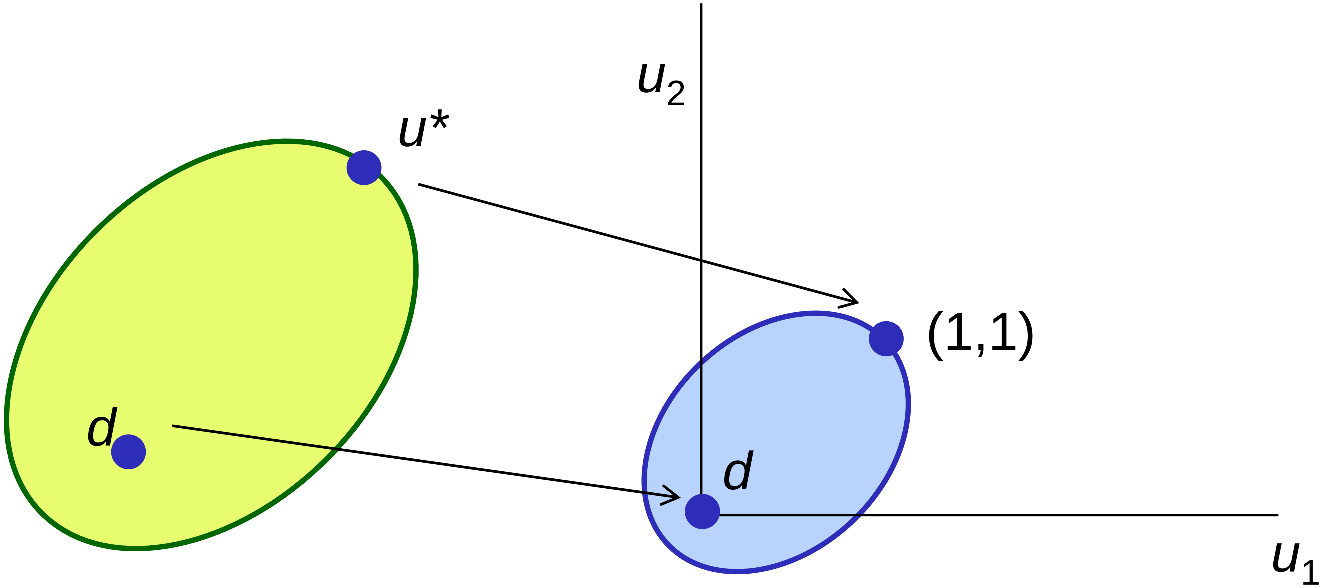
Now show that **only** the Nash solution satisfies the axioms…

Axiomatic Justification

Let u^* be the Nash solution for a given problem. Then it satisfies the axioms with respect to d. Select a transformation that sends

$$(u_1,u_2) \rightarrow (1,1), \quad (d_1,d_2) \rightarrow (0,0)$$

The transformed problem has Nash solution (1,1), by Axiom 1:



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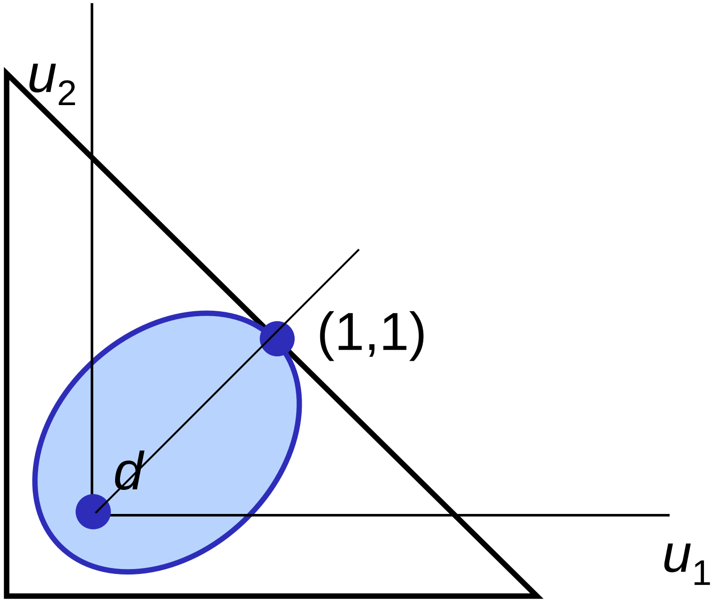
The transformed problem has Nash solution (1,1), by Axiom 1:

By Axioms 2 & 3, (1,1) is the **only** bargaining solution in the triangle:



Axiomatic Justification

Let u^* be the Nash solution for a given problem. Then it satisfies the axioms with respect to d. Select a transformation that sends

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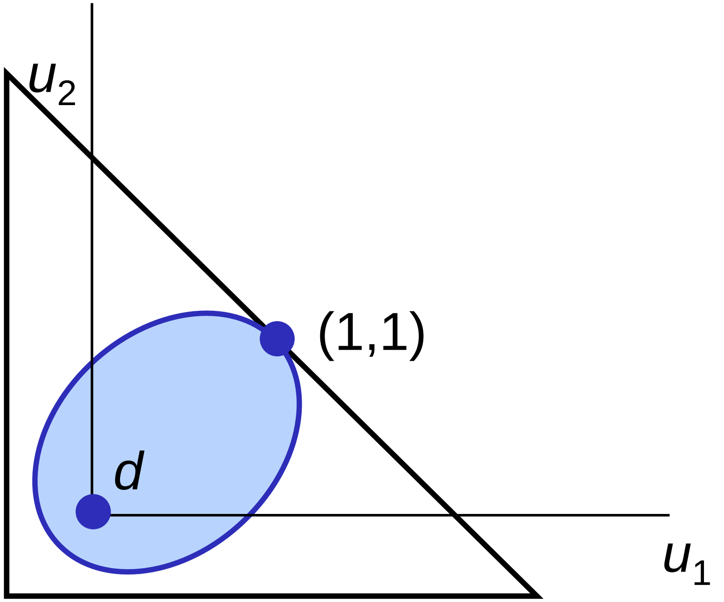


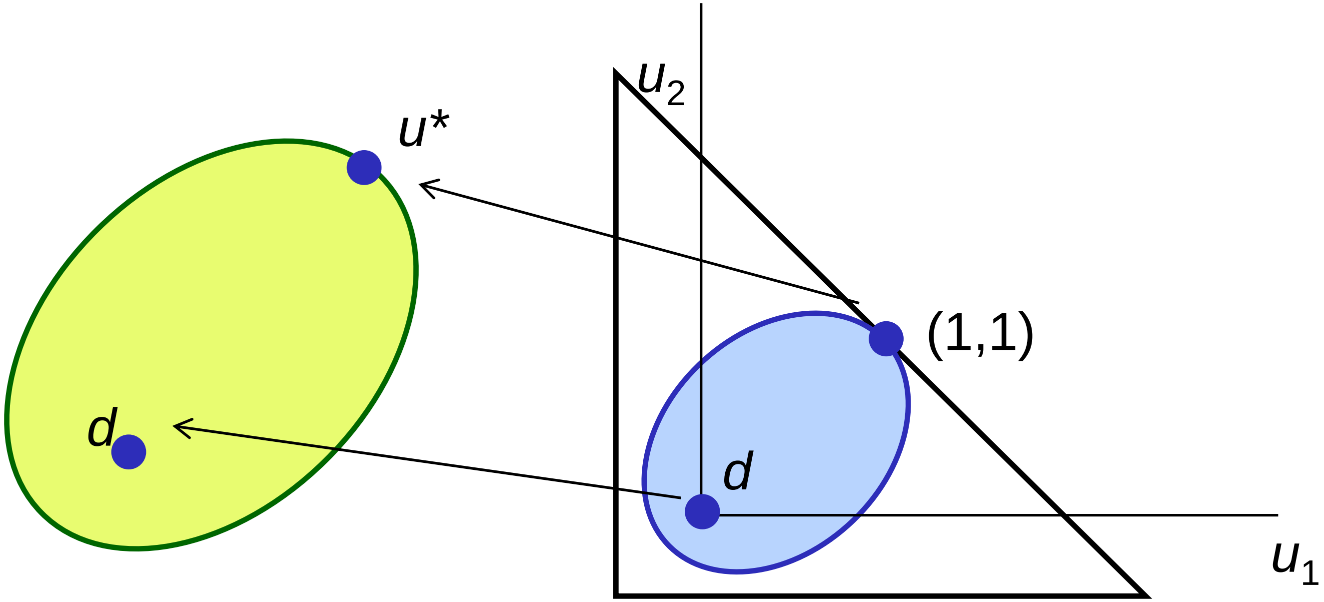
So by Axiom 4, (1,1) is the only bargaining solution in blue set.

Axiomatic Justification

Let u^* be the Nash solution for a given problem. Then it satisfies the axioms with respect to d. Select a transformation that sends

$$(u_1,u_2) \rightarrow (1,1), \quad (d_1,d_2) \rightarrow (0,0)$$

The transformed problem has Nash solution (1,1), by Axiom 1:

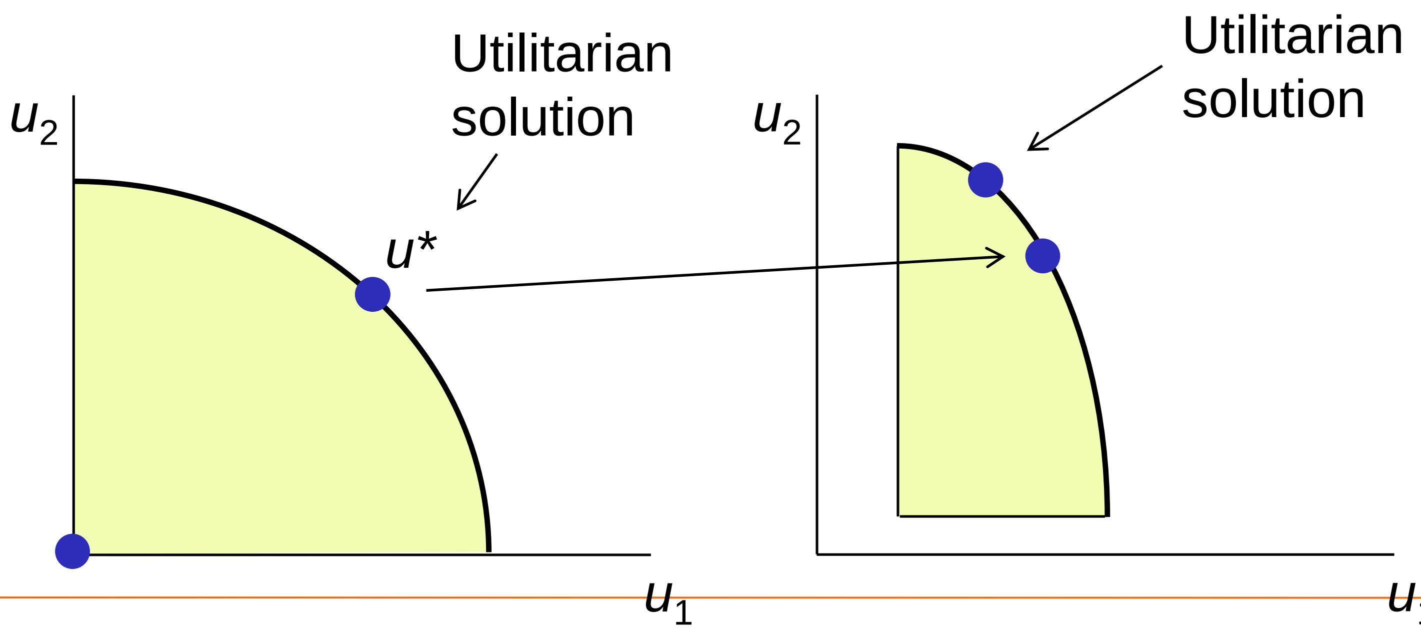


So by Axiom 4, (1,1) is the only bargaining solution in blue set.

By Axiom 1, u^* is the only bargaining solution in the original problem.

Axiomatic Justification

- **Problems** with axiomatic justification.
  - **Axiom 1** (invariance under transformation) is very strong.
  - Axiom 1 denies **interpersonal comparability**.
  - So how can it reflect moral concerns?

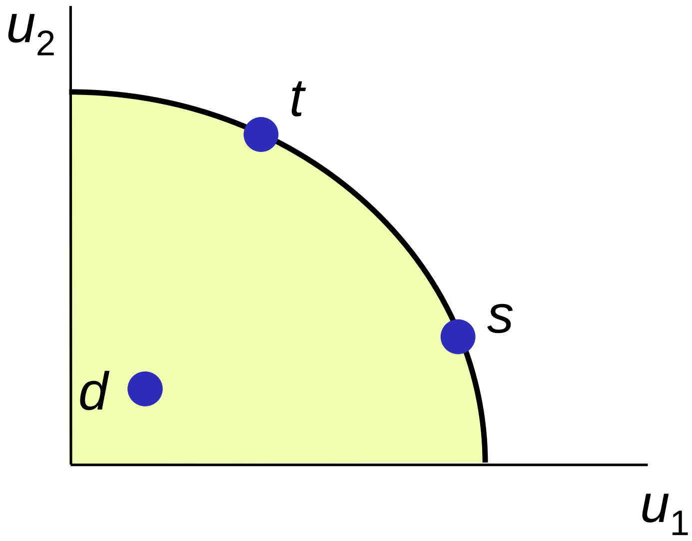


Axiomatic Justification

- **Problems** with axiomatic justification.
  - **Axiom 1** (invariance under transformation) is very strong.
  - Axiom 1 denies **interpersonal comparability**.
  - So how can it reflect moral concerns?
- Most attention has been focused on **Axiom 4** (independence of irrelevant alternatives).
  - Will address this later.

Bargaining Justification

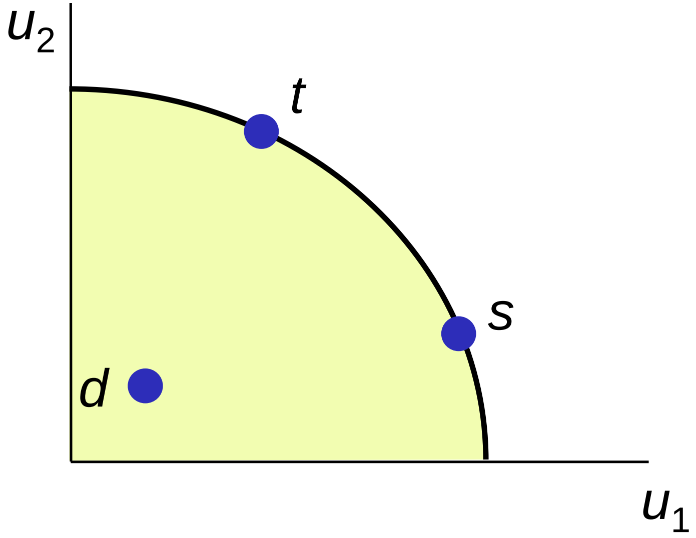
Players 1 and 2 make offers *s*, *t*.



Bargaining Justification

Players 1 and 2 make offers s, t.

Let $p = P$(player 2 will reject s), as estimated by player 1.



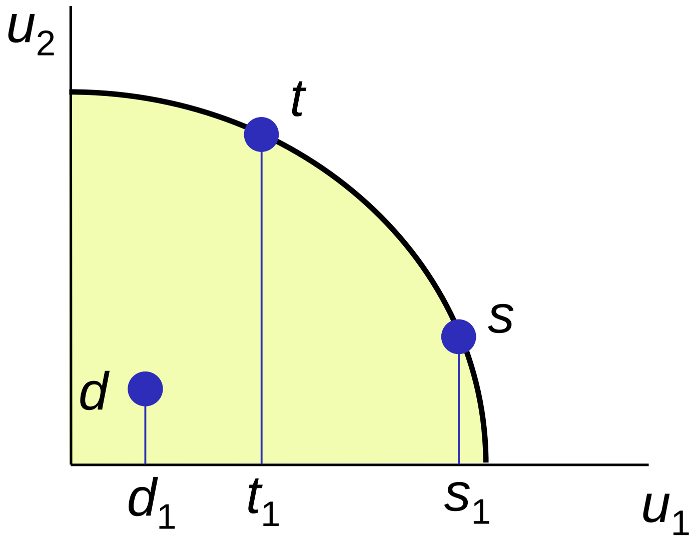
Bargaining Justification

Players 1 and 2 make offers s, t.

Let $p = P$(player 2 will reject s), as estimated by player 1.

Then player 1 will stick with s, rather than make a counteroffer, if

$$(1-p)s_1 + pd_1 \geq t_1$$



Bargaining Justification

Players 1 and 2 make offers *s*, *t*.

Let $p = P(\text{player 2 will reject } s)$, as estimated by player 1.

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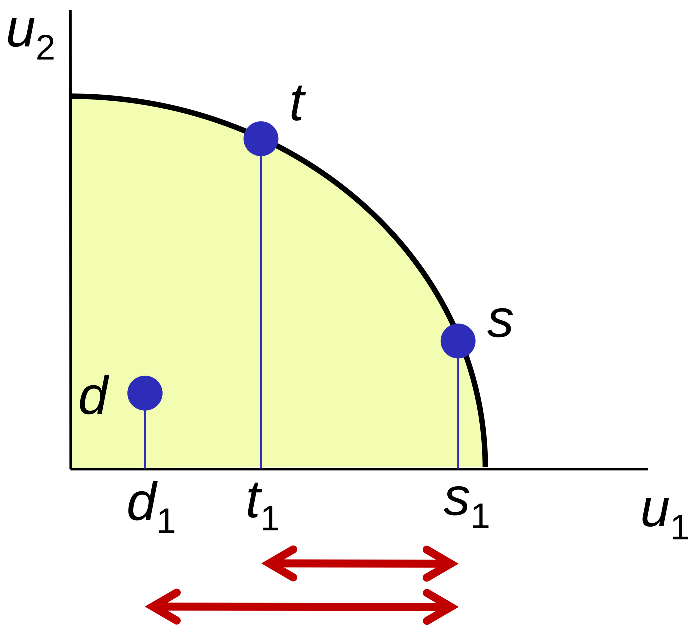


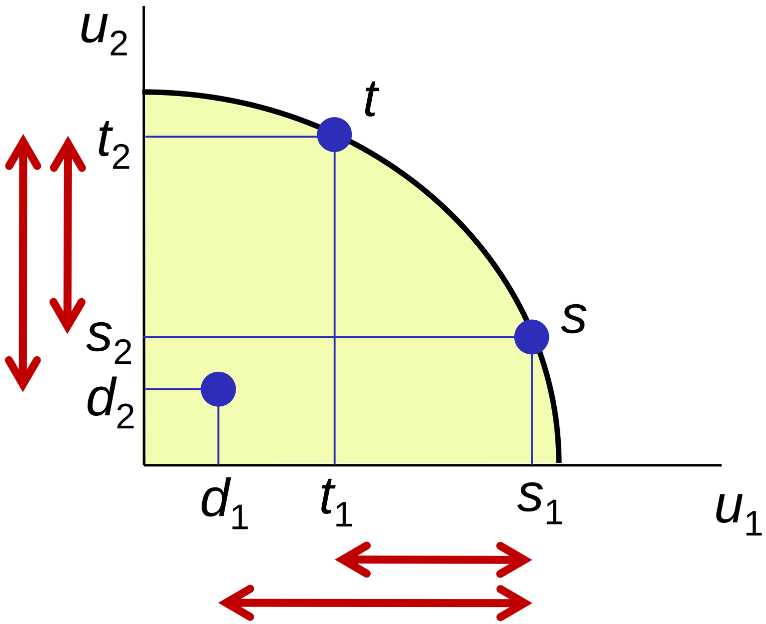
So player 1 will stick with *s* if

$$p \leq \frac{s_1 - t_1}{s_1 - d_1} = r_1$$

Bargaining Justification

It is rational for player 1 to make a counteroffer s', rather than player 2, if

$$r_1 = \frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2} = r_2$$



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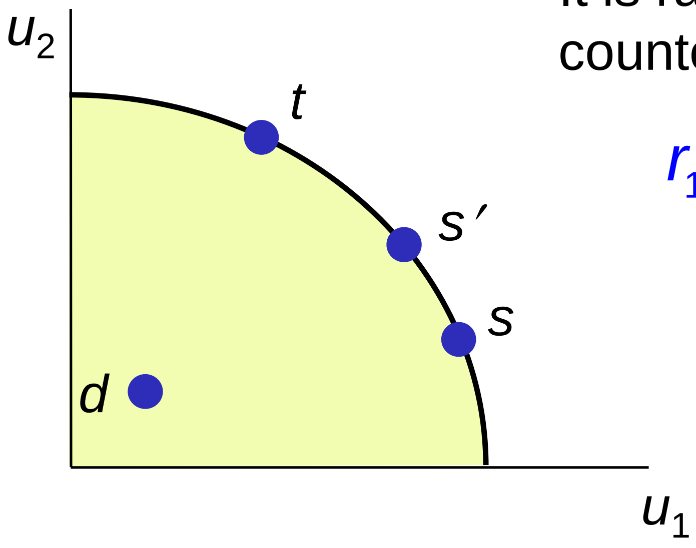


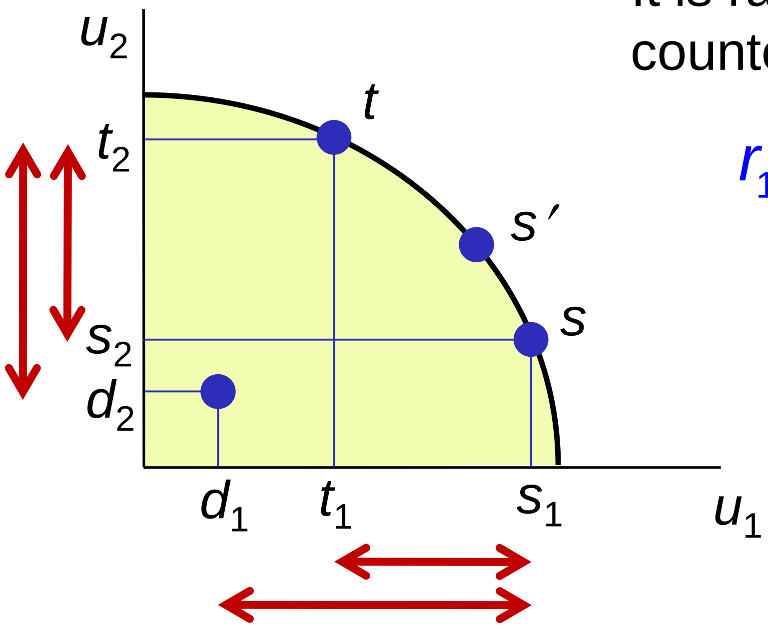
It is rational for player 2 to make the next counteroffer if

$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

Bargaining Justification

It is rational for player 1 to make a counteroffer s', rather than player 2, if

$$r_1 = \frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2} = r_2$$



It is rational for player 2 to make the next counteroffer if

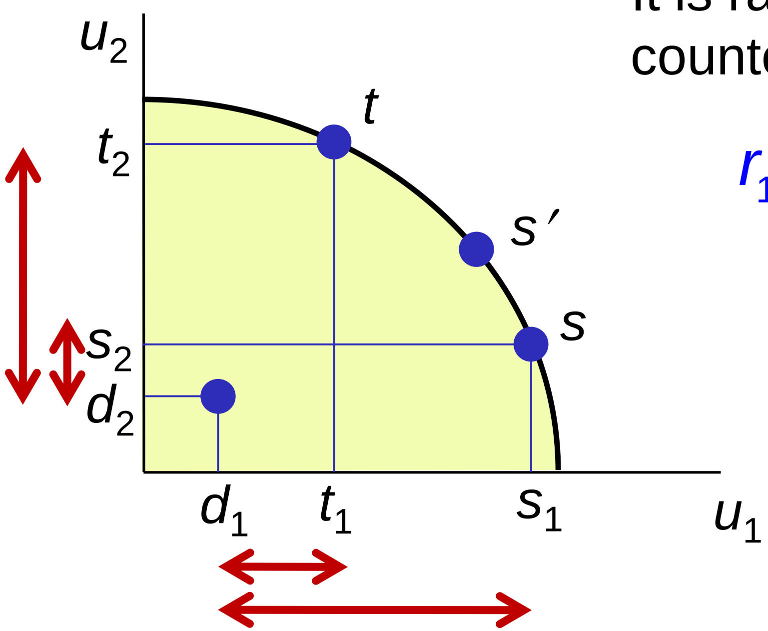
$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

But $$\frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2}$$

Bargaining Justification

It is rational for player 1 to make a counteroffer s', rather than player 2, if

$$r_1 = \frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2} = r_2$$



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$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

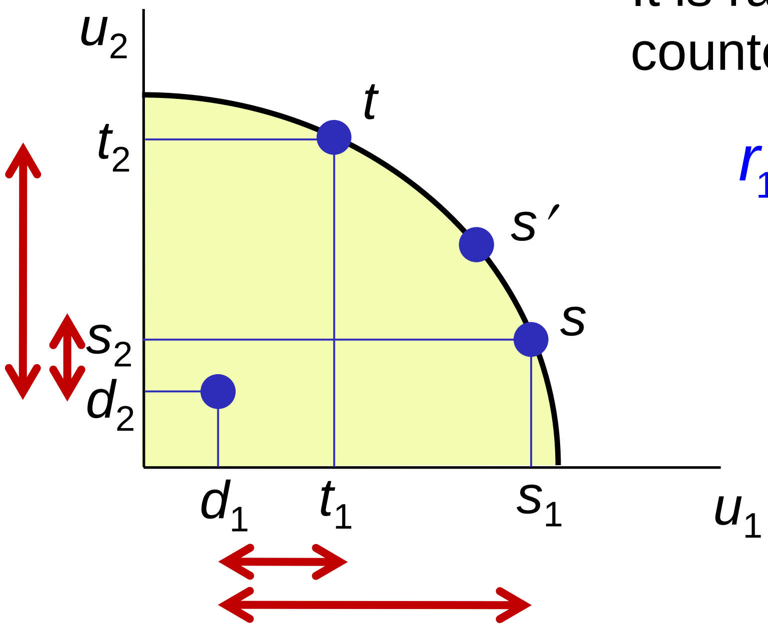
But

$$\frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2}$$

$$\Longleftrightarrow \quad \frac{t_1 - d_1}{s_1 - d_1} \ge \frac{s_2 - d_2}{t_2 - d_2}$$

Bargaining Justification

So we have $(s_1 - d_1)(s_2 - d_2) \le (t_1 - d_1)(t_2 - d_2)$



It is rational for player 2 to make the next counteroffer if

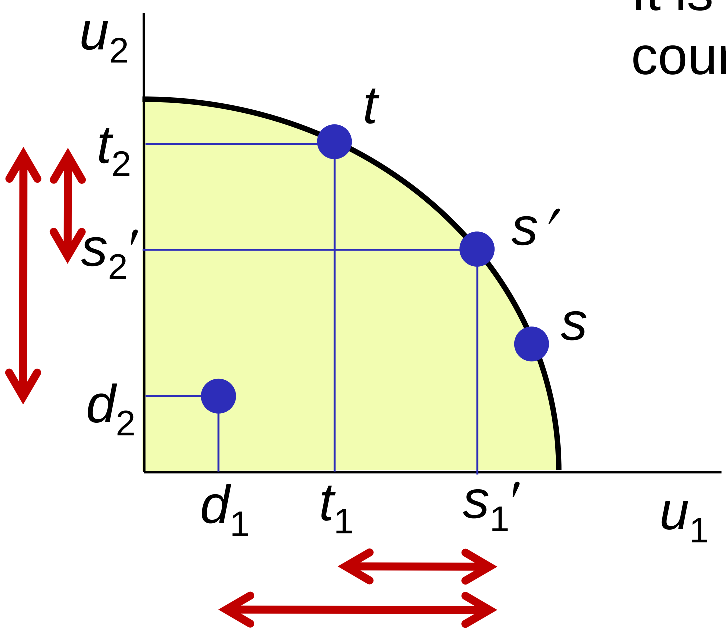
$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

But
$$\frac{s_1 - t_1}{s_1 - d_1} \le \frac{t_2 - s_2}{t_2 - d_2}$$

$$\Longleftrightarrow \frac{t_1 - d_1}{s_1 - d_1} \ge \frac{s_2 - d_2}{t_2 - d_2}$$

Bargaining Justification

So we have $$(s_1 - d_1)(s_2 - d_2) \le (t_1 - d_1)(t_2 - d_2)$$



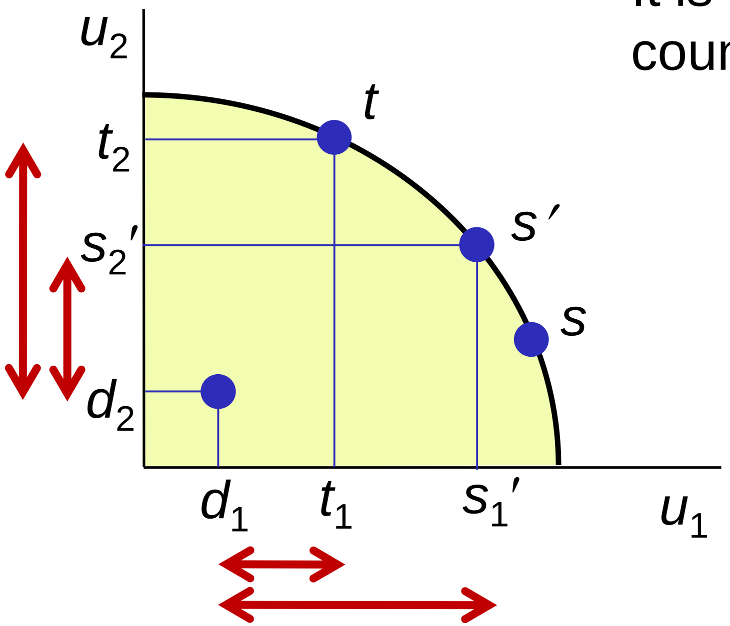
It is rational for player 2 to make the next counteroffer if

$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

Similarly $$\frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2}$$

Bargaining Justification

So we have $$(s_1 - d_1)(s_2 - d_2) \le (t_1 - d_1)(t_2 - d_2)$$



It is rational for player 2 to make the next counteroffer if

$$r_1' = \frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2} = r_2'$$

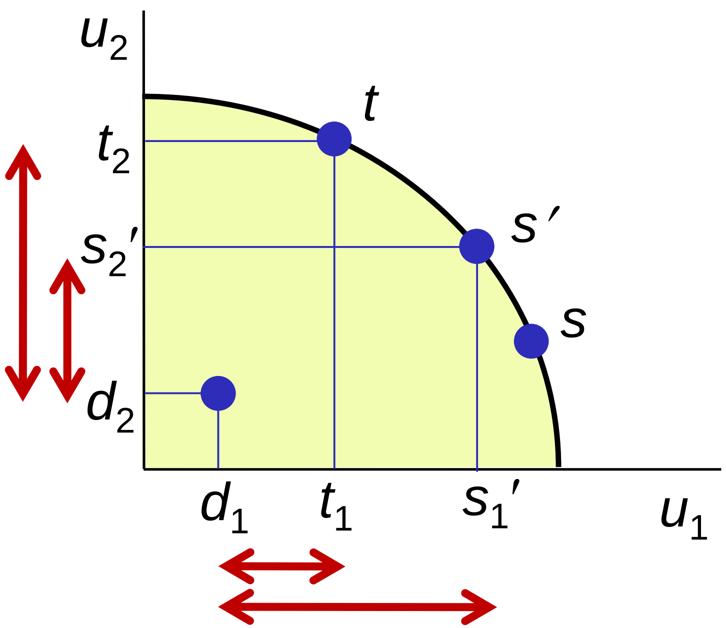
Similarly $$\frac{s_1' - t_1}{s_1' - d_1} \ge \frac{t_2 - s_2'}{t_2 - d_2}$$

$$\Longleftrightarrow \frac{t_1 - d_1}{s_1' - d_1} \le \frac{s_2' - d_2}{t_2 - d_2}$$

Bargaining Justification

So we have $(s_1 - d_1)(s_2 - d_2) \le (t_1 - d_1)(t_2 - d_2)$

and we have $(t_1 - d_1)(t_2 - d_2) \le (s_1' - d_1)(s_2' - d_2)$



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So we have $(s_1 - d_1)(s_2 - d_2) \le (t_1 - d_1)(t_2 - d_2)$

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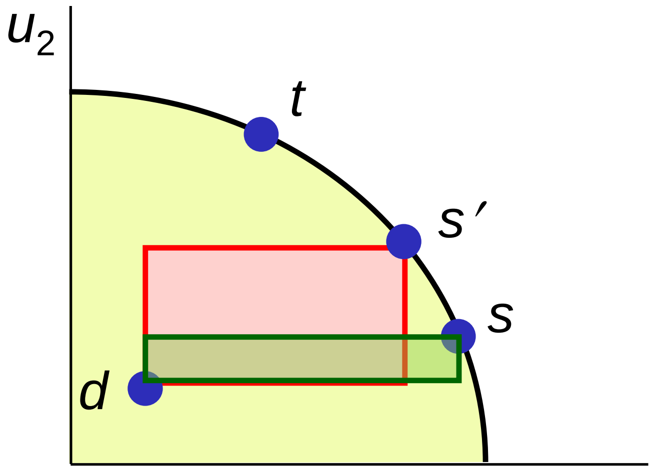

This implies an improvement in the Nash social welfare function

Bargaining Justification

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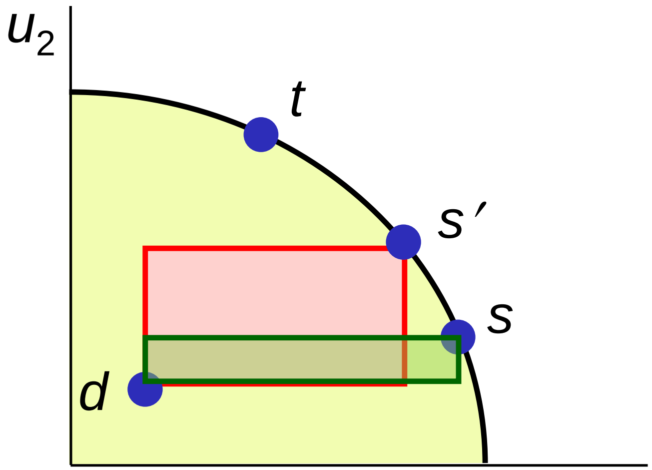


This implies an improvement in the Nash social welfare function.

Given a minimum distance between offers, continued bargaining converges to Nash solution.

Bargaining Justification

Problem with bargaining justifications.

Why should a bargaining procedure that is rational from an **individual** viewpoint result in a **just distribution?**

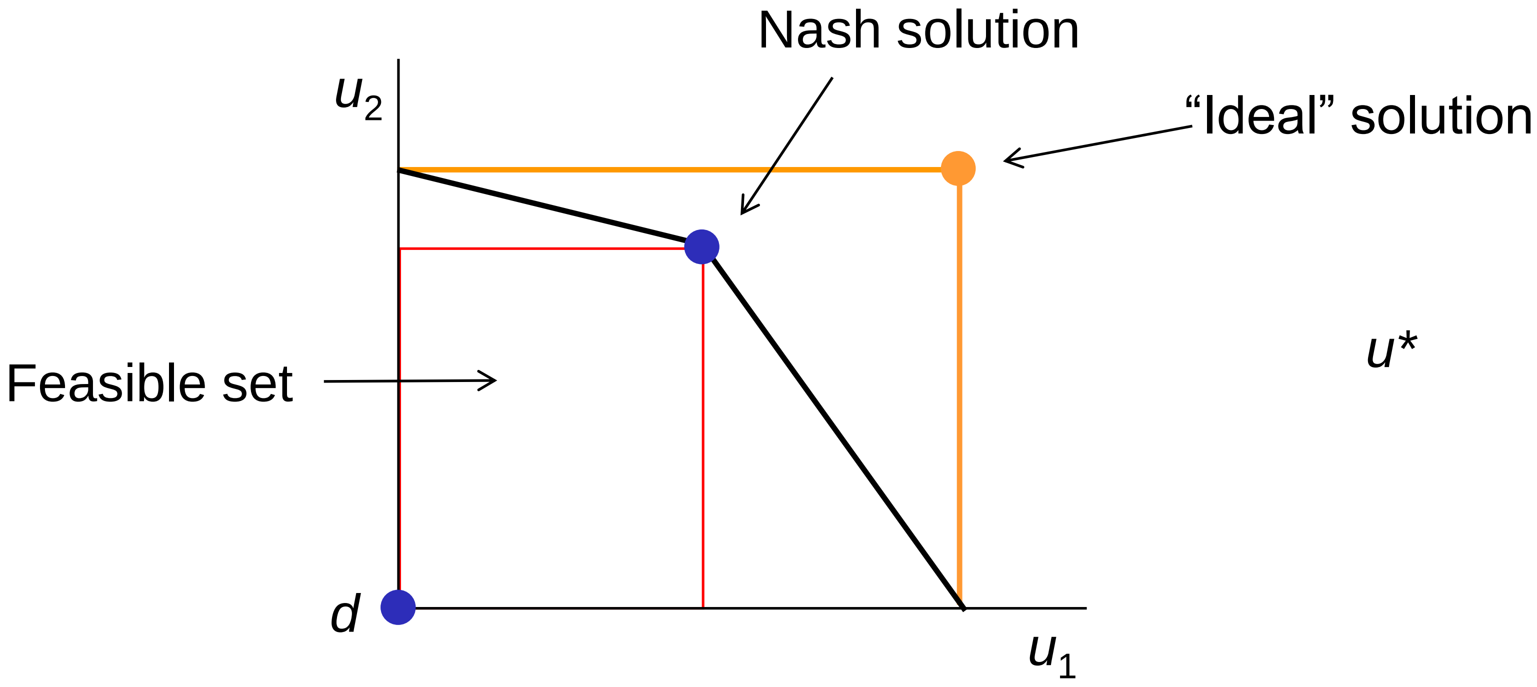
Why should "**procedural justice**" = **justice**? For example, is the outcome of bargaining in a free market necessarily just?

A deep question in political theory.

Also applies to **political districting analysis**, currently a hot topic in USA.

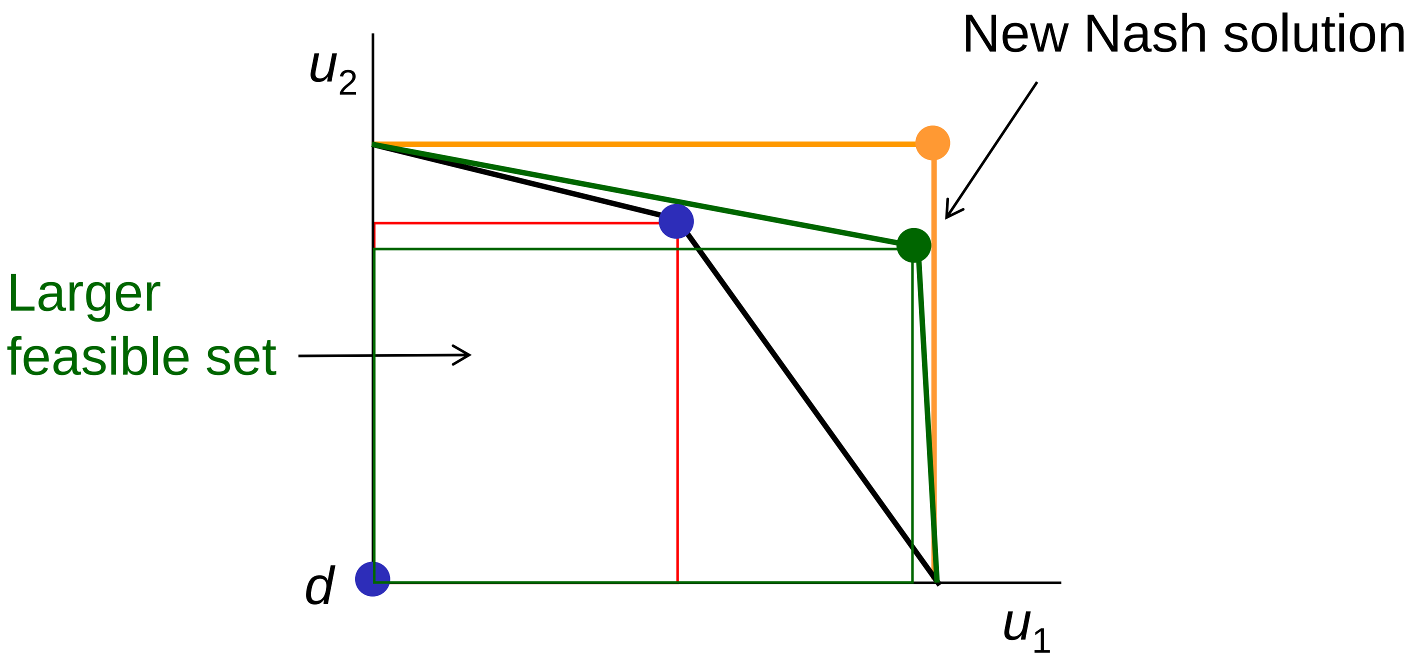
Raiffa-Kalai-Smorodinsky Bargaining Solution

- This approach begins with a critique of the Nash bargaining solution.



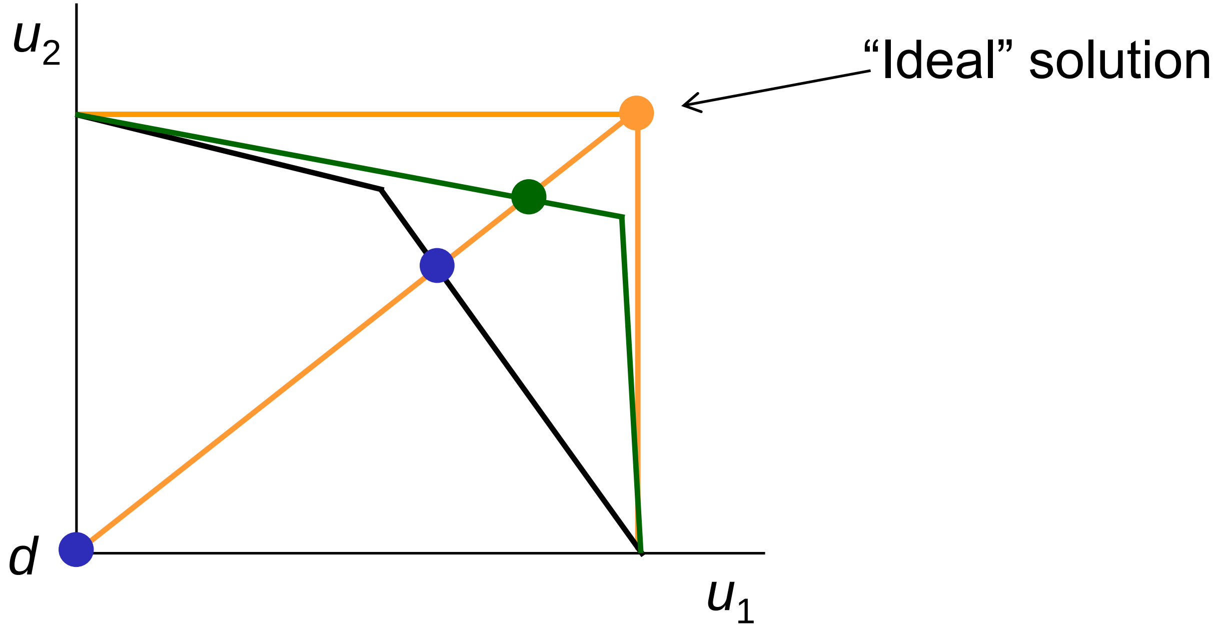
Raiffa-Kalai-Smorodinsky Bargaining Solution

- This approach begins with a critique of the Nash bargaining solution.
  - The new Nash solution is **worse** for player 2 even though the feasible set is **larger**.



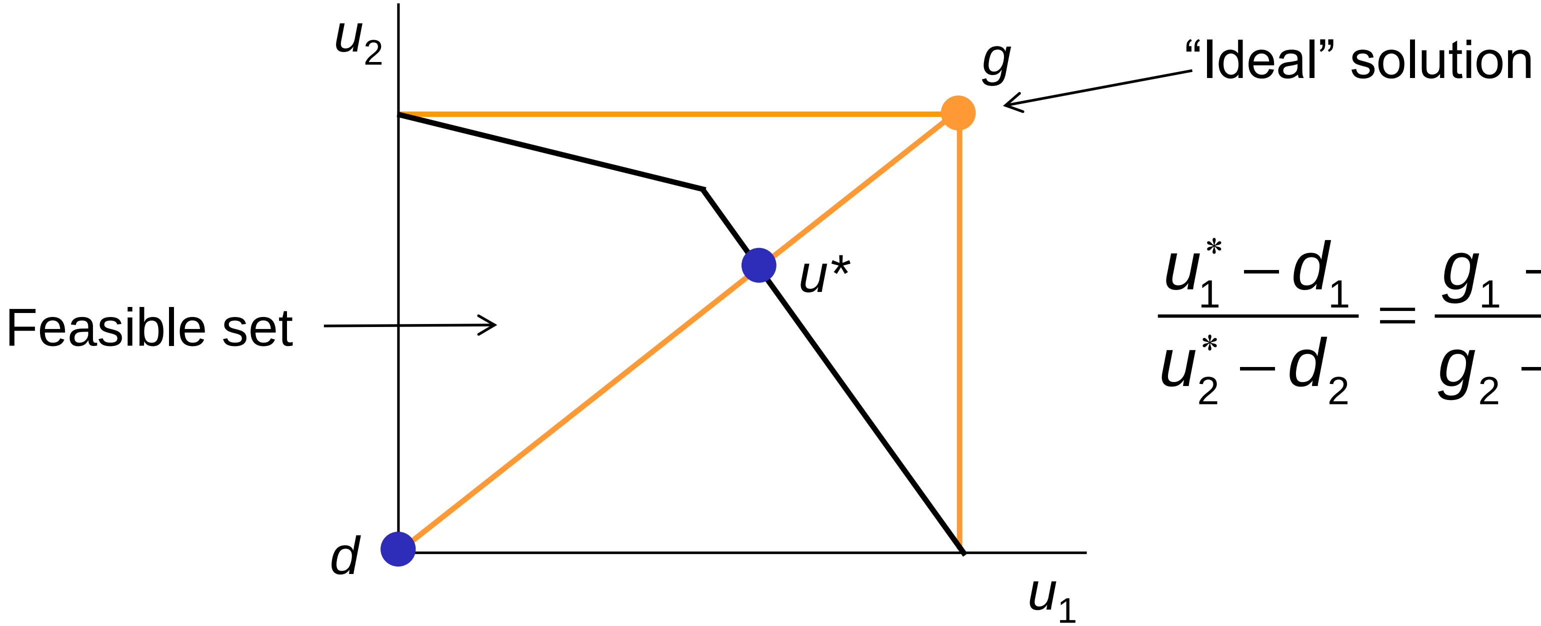
Raiffa-Kalai-Smorodinsky Bargaining Solution

- **Proposal**: Bargaining solution is pareto optimal point on line from *d* to ideal solution.



Raiffa-Kalai-Smorodinsky Bargaining Solution

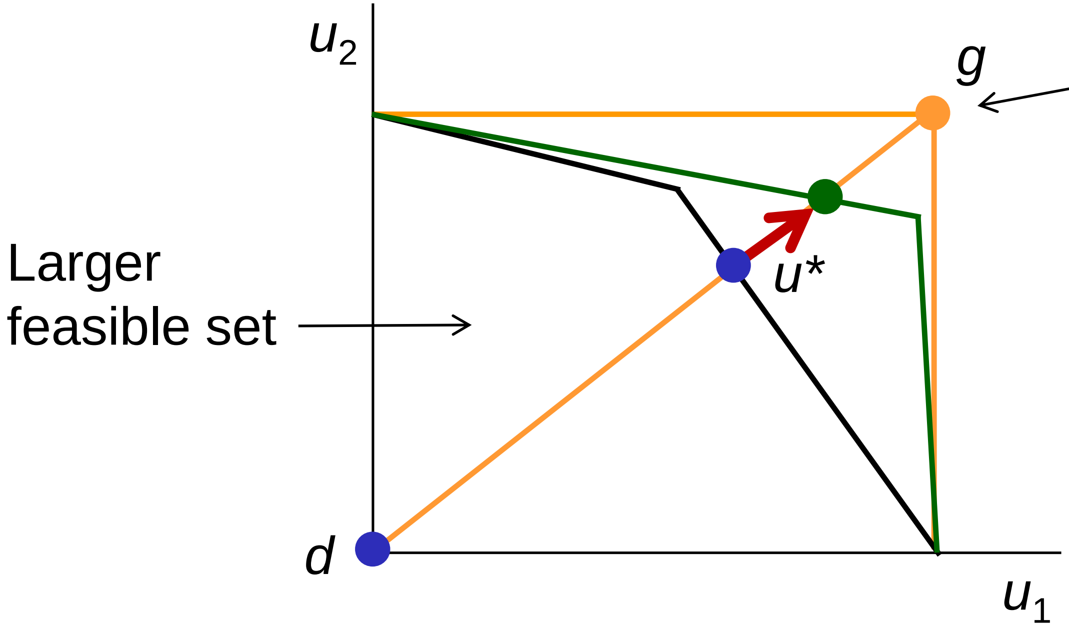
- **Proposal**: Bargaining solution is pareto optimal point on line from *d* to ideal solution.
  - The players receive an equal fraction of their possible utility gains.



$$\frac{u_1^* - d_1}{u_2^* - d_2} = \frac{g_1 - d_1}{g_2 - d_2}$$

Raiffa-Kalai-Smorodinsky Bargaining Solution

- **Proposal**: Bargaining solution is pareto optimal point on line from *d* to ideal solution.
  - Replace Axiom 4 with **Axiom 4′ (Monotonicity)**: A larger feasible set with same ideal solution results in a bargaining solution that is better (or no worse) for all players.



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Raiffa-Kalai-Smorodinsky Bargaining Solution

- **Optimization model**.
  - Not an optimization problem over original feasible set (we gave up Axiom 4).
  - But it is an optimization problem (pareto optimality) over the line segment from *d* to ideal solution.

$$\max \sum_i u_i$$

$$(g_1 - d_1)(u_i - d_i) = (g_i - d_i)(u_1 - d_1), \quad \text{all } i$$

$$u \in S$$

$$\frac{u_1^* - d_1}{u_2^* - d_2} = \frac{g_1 - d_1}{g_2 - d_2}$$

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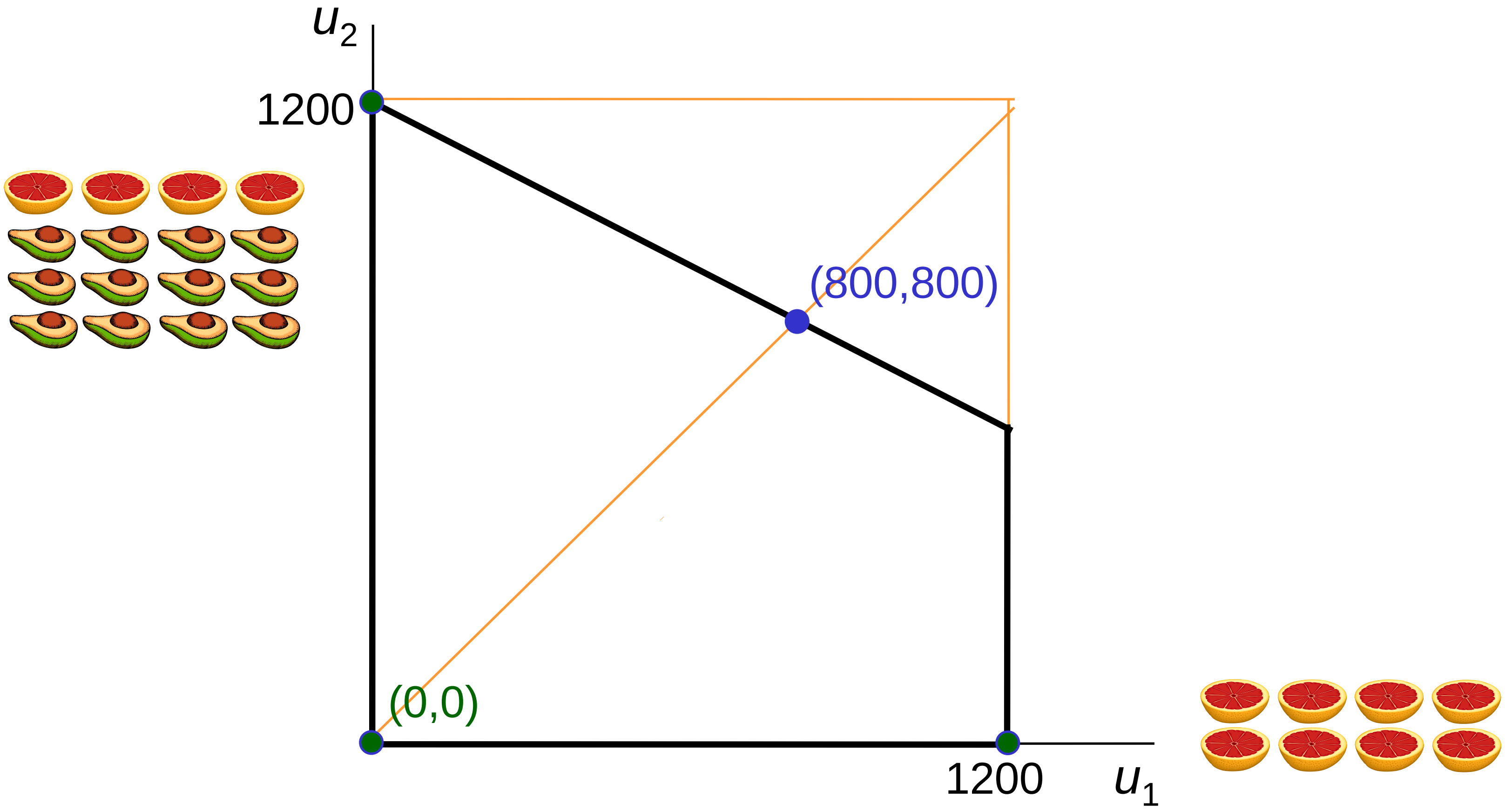
Linear constraint

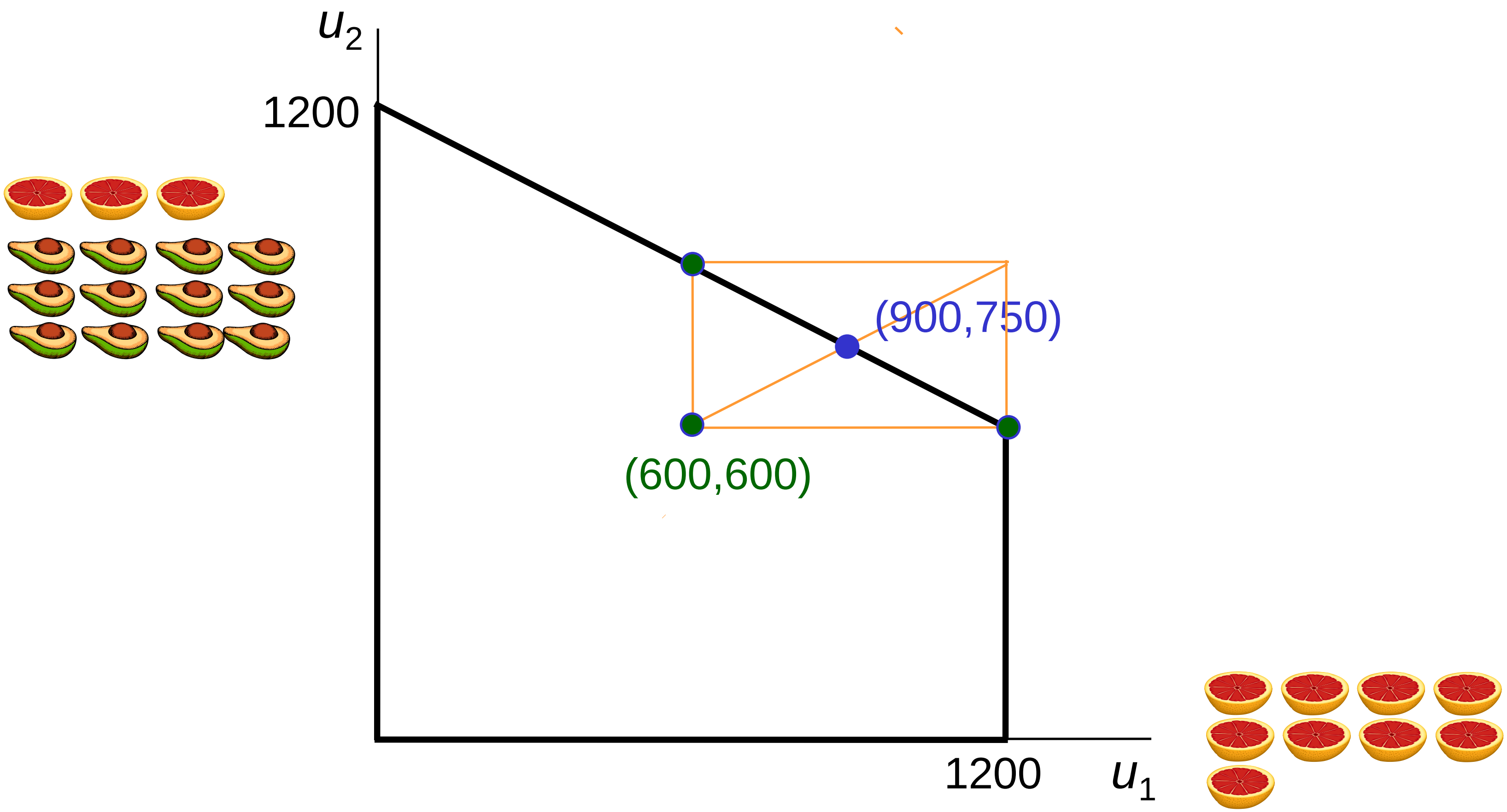
Raiffa-Kalai-Smorodinsky Bargaining Solution

From Zero



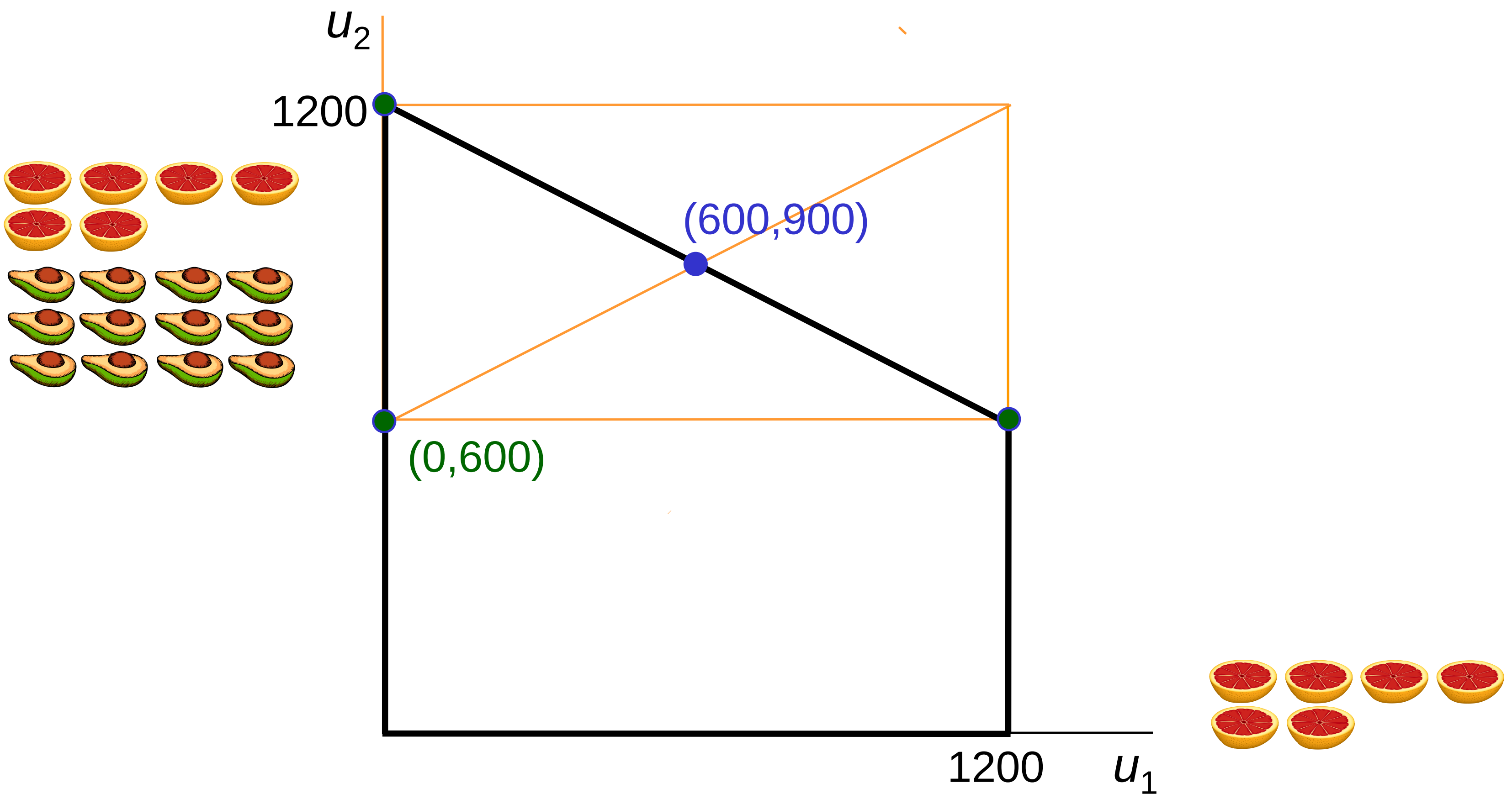
Raiffa-Kalai-Smorodinsky Bargaining Solution

From Equality



Raiffa-Kalai-Smorodinsky Bargaining Solution

From Strong Pareto Set



Axiomatic Justification

- **Axiom 1**. Invariance under transformation.
- **Axiom 2.** Pareto optimality.
- **Axiom 3.** Symmetry.
- **Axiom 4′.** Monotonicity.

Axiomatic Justification

Theorem. Exactly one solution satisfies Axioms 1-4′, namely the RKS bargaining solution.

Proof (2 dimensions).

Easy to show that RKS solution satisfies the axioms.

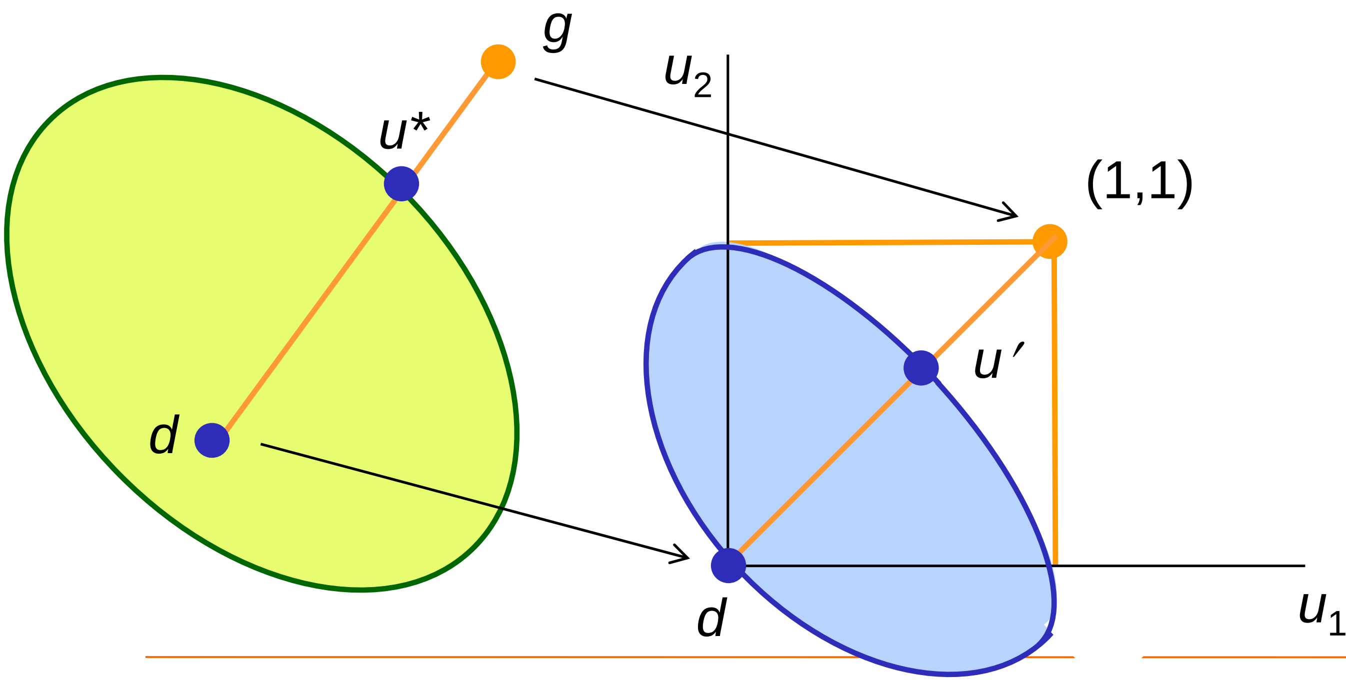
Now show that **only** the RKS solution satisfies the axioms.

Axiomatic Justification

Let u^* be the RKS solution for a given problem. Then it satisfies the axioms with respect to d. Select a transformation that sends

$$(g_1,g_2) \rightarrow (1,1), \quad (d_1,d_2) \rightarrow (0,0)$$

The transformed problem has RKS solution u', by Axiom 1:



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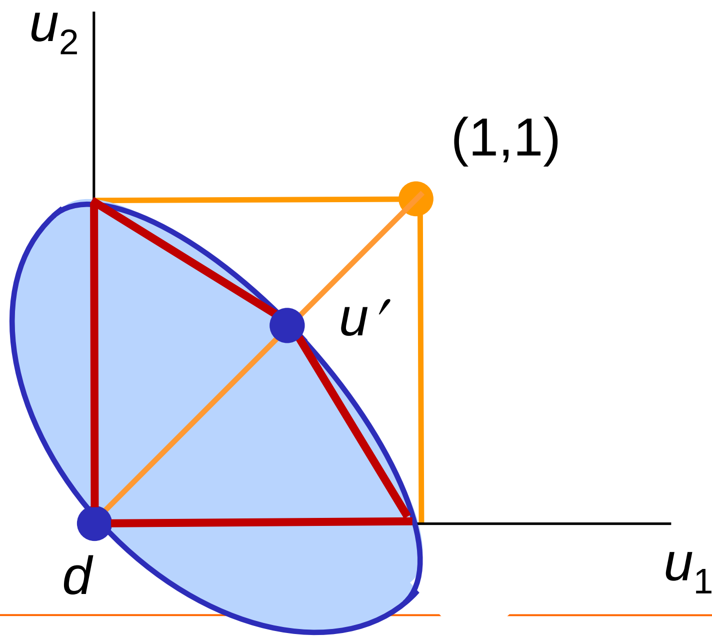
By Axioms 2 & 3, u' is the **only** bargaining solution in the red polygon:



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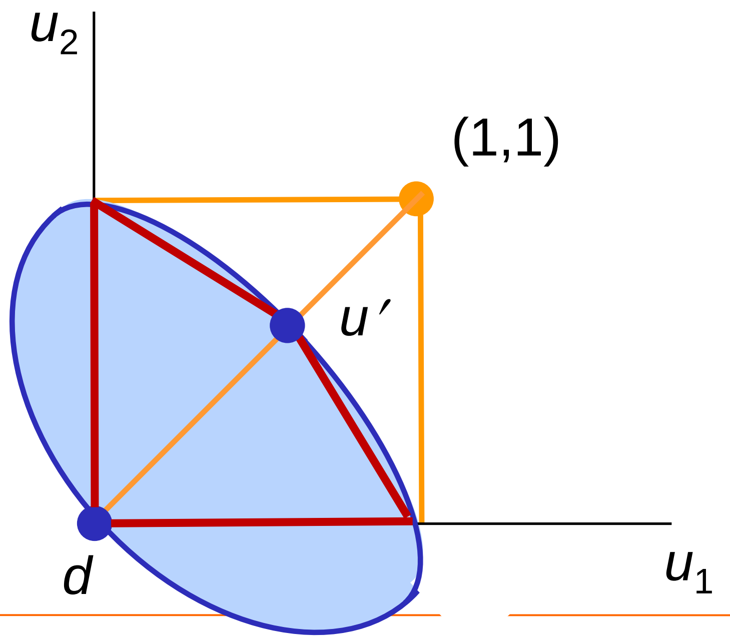

The red polygon lies inside blue set. So by Axiom 4′, its bargaining solution is no better than bargaining solution on blue set. So u' is the only bargaining solution on blue set.

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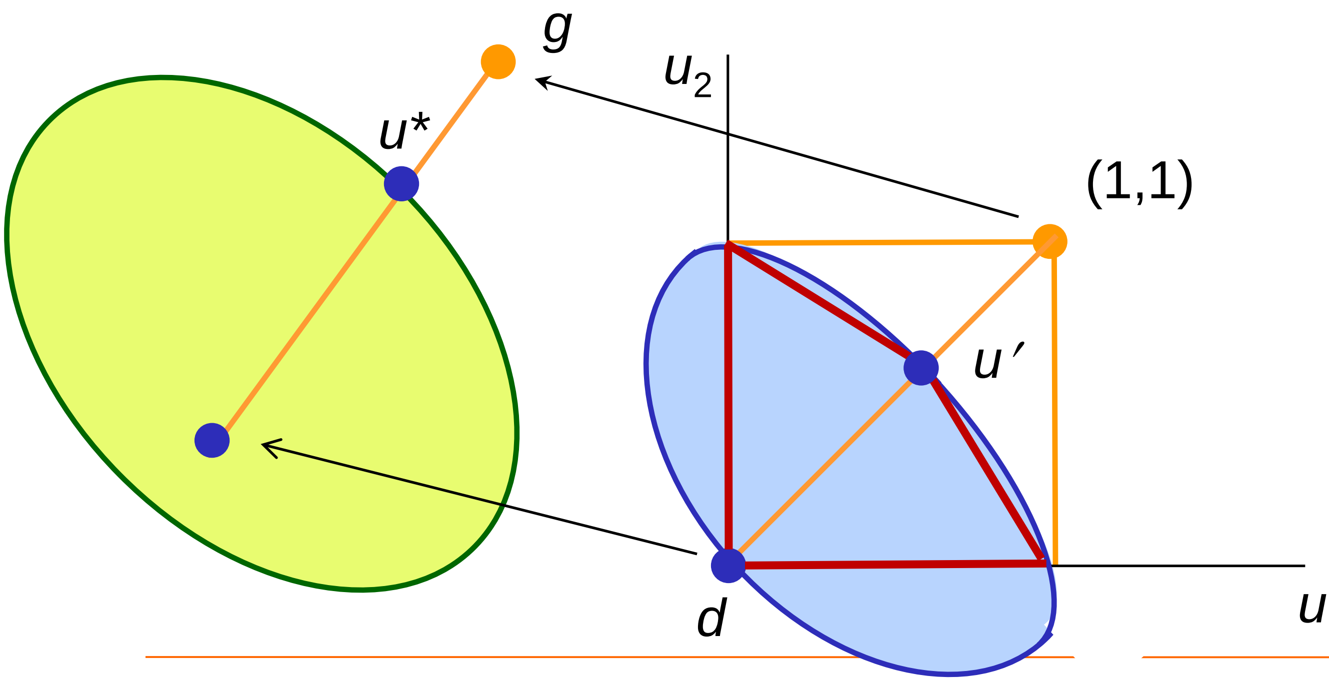


By Axiom 1, u^* is the only bargaining solution in the original problem.

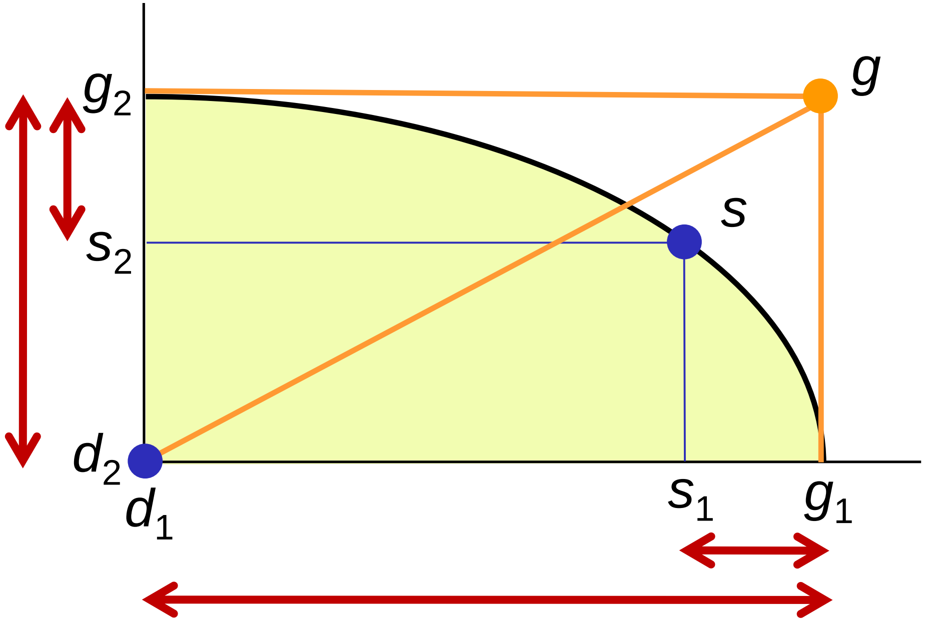
Axiomatic Justification

- **Problems** with axiomatic justification.
  - **Axiom 1** is still in effect.
  - It denies **interpersonal comparability**.
  - Dropping Axiom 4 sacrifices optimization of a social welfare function.
  - This may not be necessary if Axiom 1 is rejected.
  - Needs modification for > 2 players (more on this shortly).

Bargaining Justification

Resistance to an agreement *s* depends on sacrifice relative to sacrifice under no agreement. Here, player 2 is making a larger relative sacrifice:

$$\frac{g_1 - s_1}{g_1 - d_1} \le \frac{g_2 - s_2}{g_2 - d_2}$$



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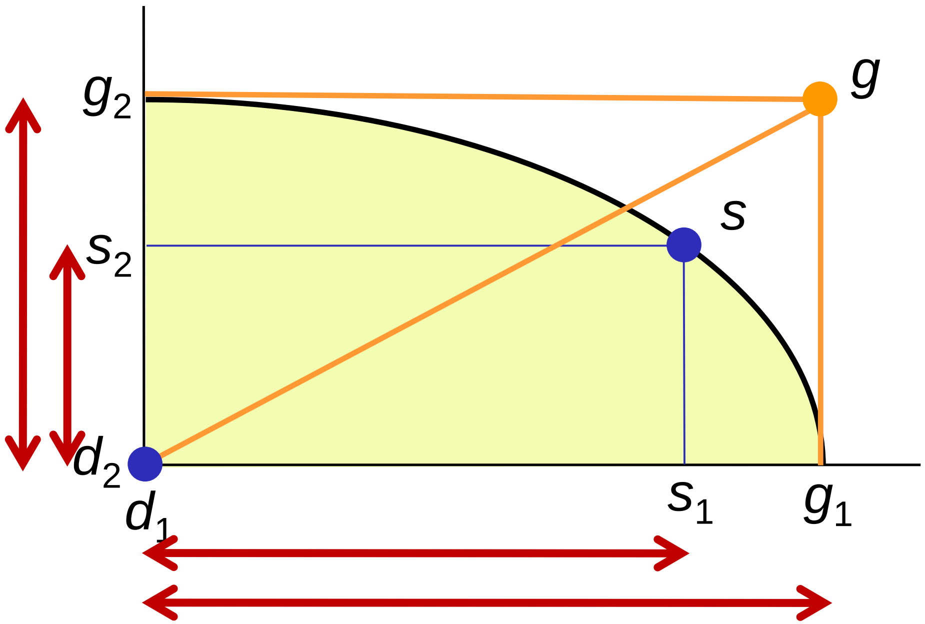

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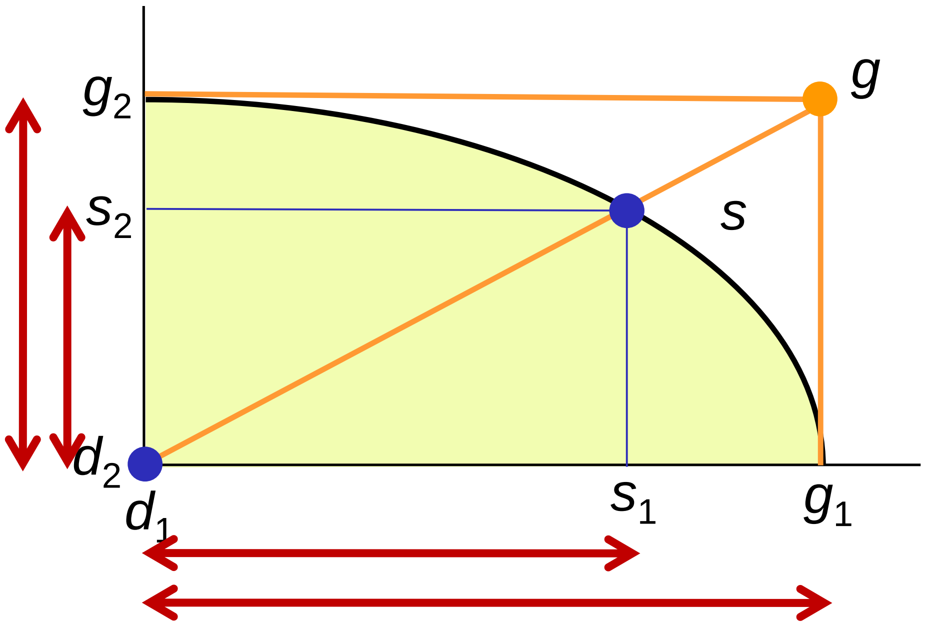

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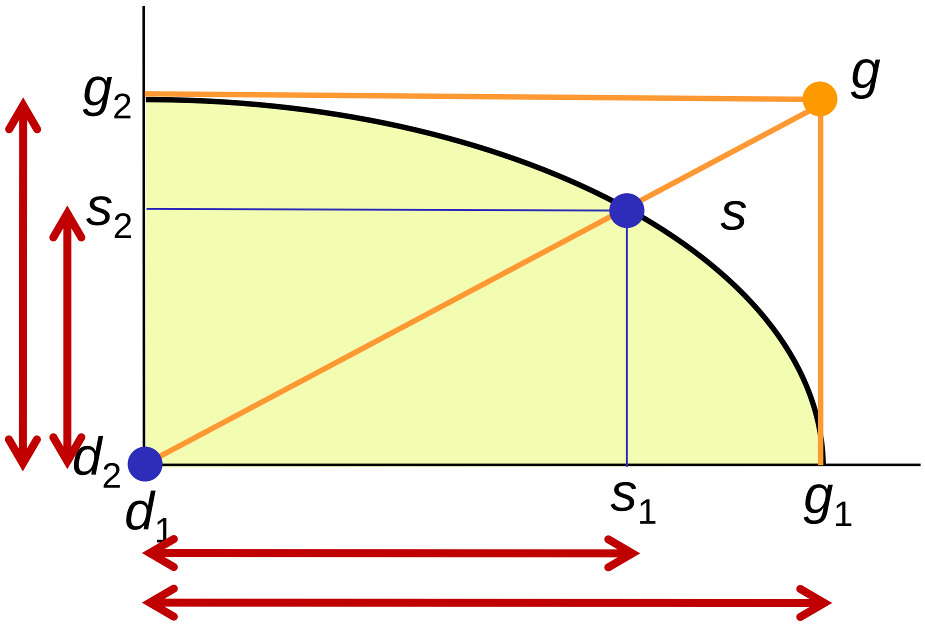
which is achieved by RKS point.

Bargaining Justification

This is the **Rawlsian social contract** argument applied to **gains relative to the ideal**.



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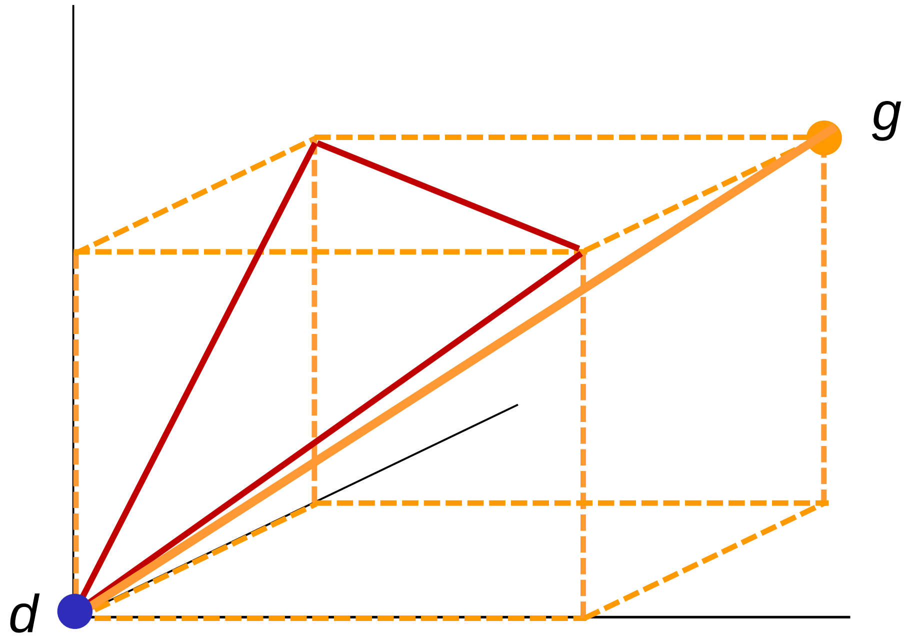
Problem with RKS Solutioon

- However, the RKS solution is Rawlsian only for **2 players**.
  - In fact, RKS leads to counterintuitive results for 3 players.



Red triangle is feasible set.

RKS point is *d* !

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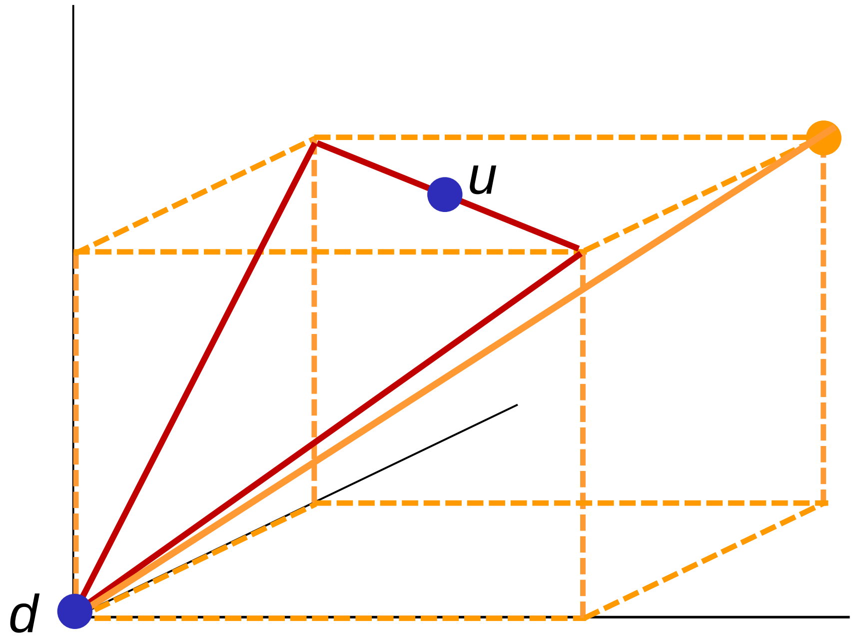
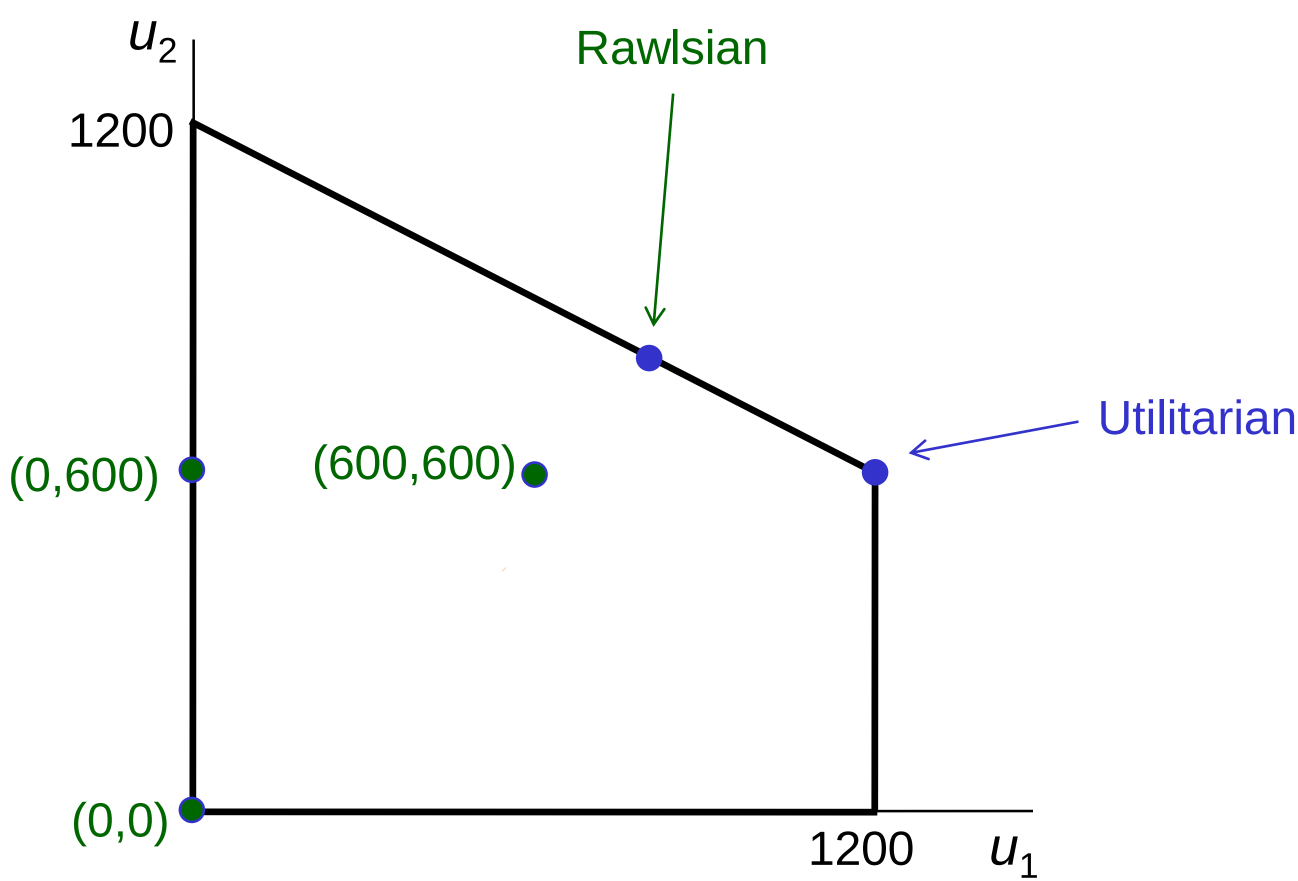


Red triangle is feasible set.

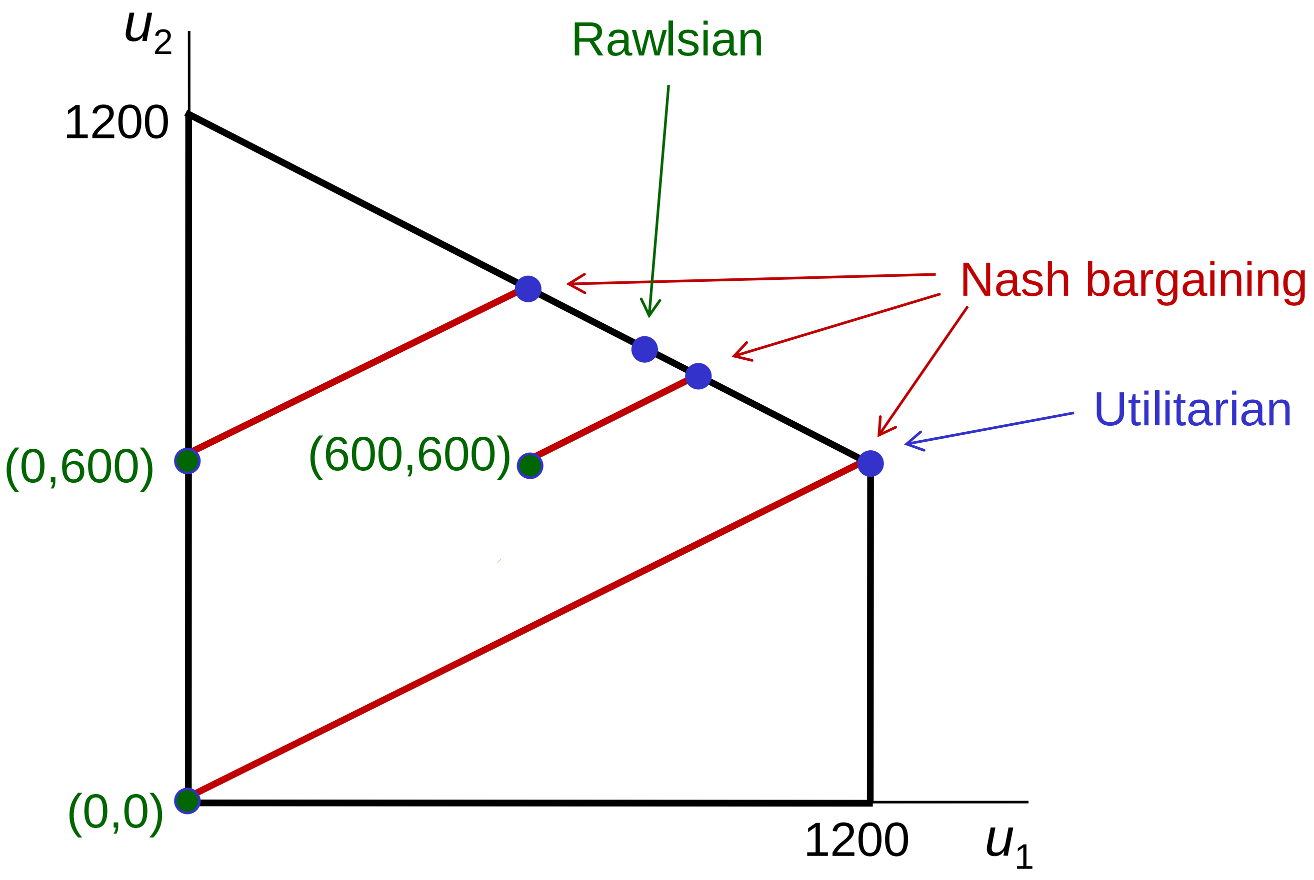
RKS point is *d* !

Rawlsian point is *u.*

Summary

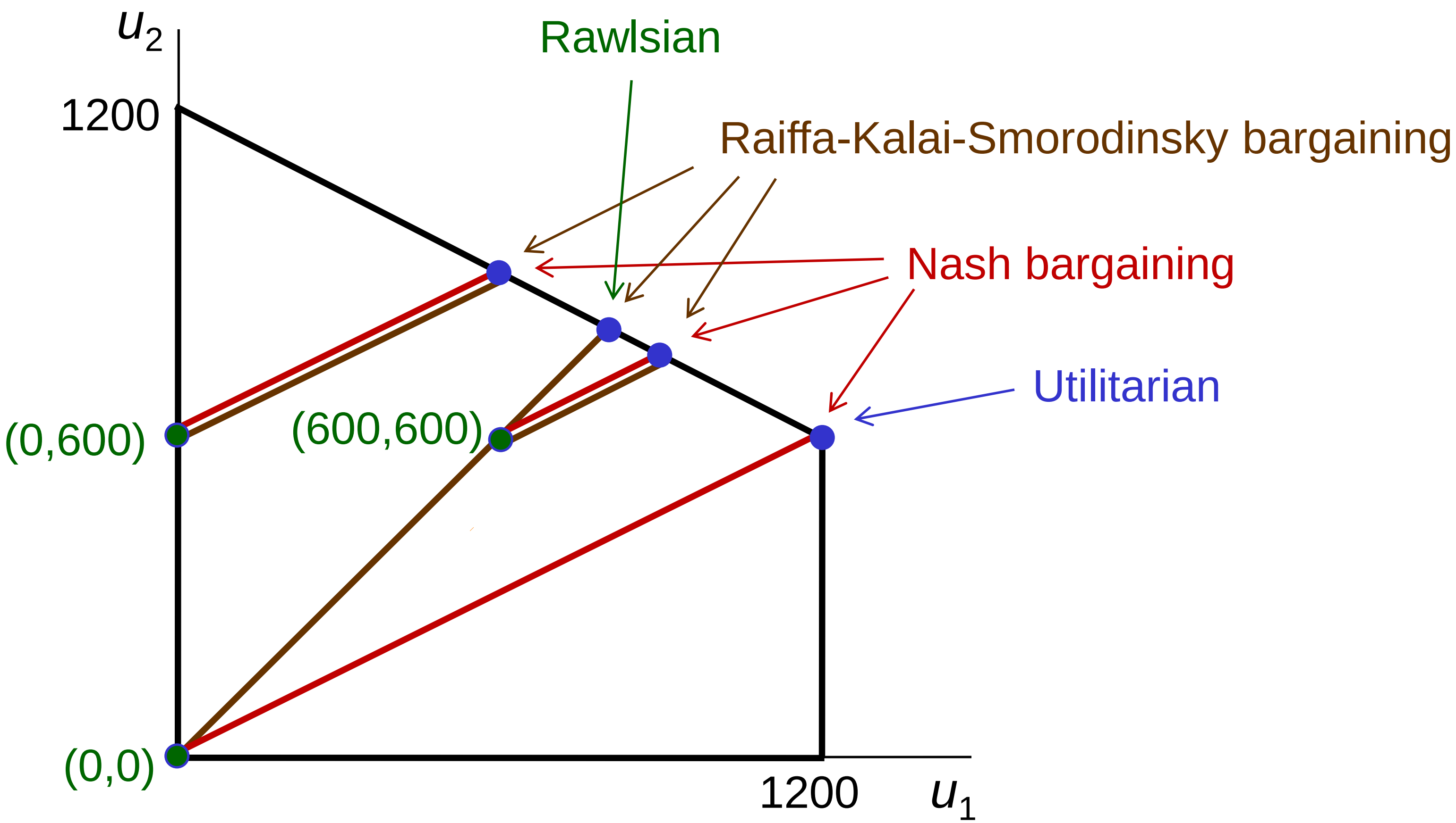


Summary



u_2
1200
Rawlsian
Nash bargaining
Utilitarian
(0,600)
(600,600)
(0,0)
1200
u_1

Summary



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Combining Equity and Efficiency

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  - Or cure dandruff, which afflicts about 3 billion people, or half the population (utilitarian solution).

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Combining Equity and Efficiency

- Utilitarian and Rawlsian distributions seem **too extreme** in practice.
  - How to combine them?

- **One proposal:**
  - Maximize welfare of **worst off** (Rawlsian)...
  - …until this requires **undue sacrifice** from others
  - That is, until **marginal utility cost** of helping the worst off becomes extreme.

Combining Equity and Efficiency

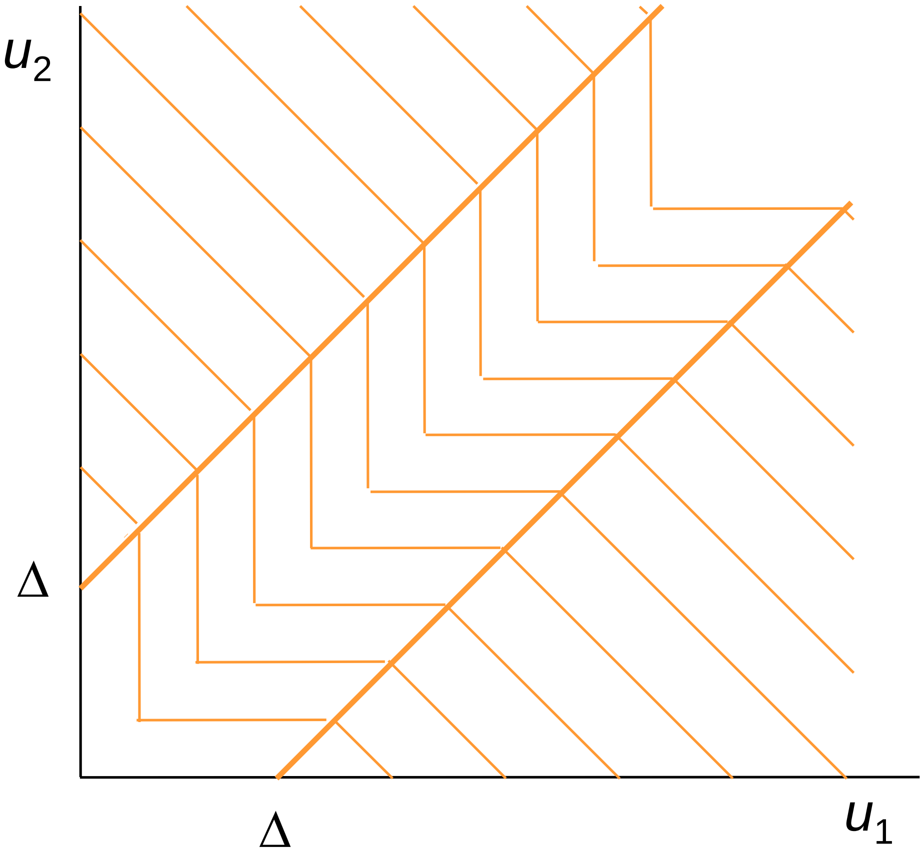
- In particular:
  - Design a **social welfare function (SWF)** to be maximized
  - Switch from **Rawlsian** to **utilitarian** when **inequality** exceeds Δ**.**

Combining Equity and Efficiency

- In particular:
  - Design a **social welfare function (SWF)** to be maximized
  - Switch from **Rawlsian** to **utilitarian** when **inequality** exceeds Δ.
  - Build mixed integer programming model.
  - Let u_i = utility allocated to person i
- For 2 persons:
  - Maximize $\min_i \{u_1, u_2\}$ (Rawlsian) when $|u_1 - u_2| \leq \Delta$
  - Maximize $u_1 + u_2$ (utilitarian) when $|u_1 - u_2| > \Delta$

Two-person Model

Contours of **social welfare function** for 2 persons.



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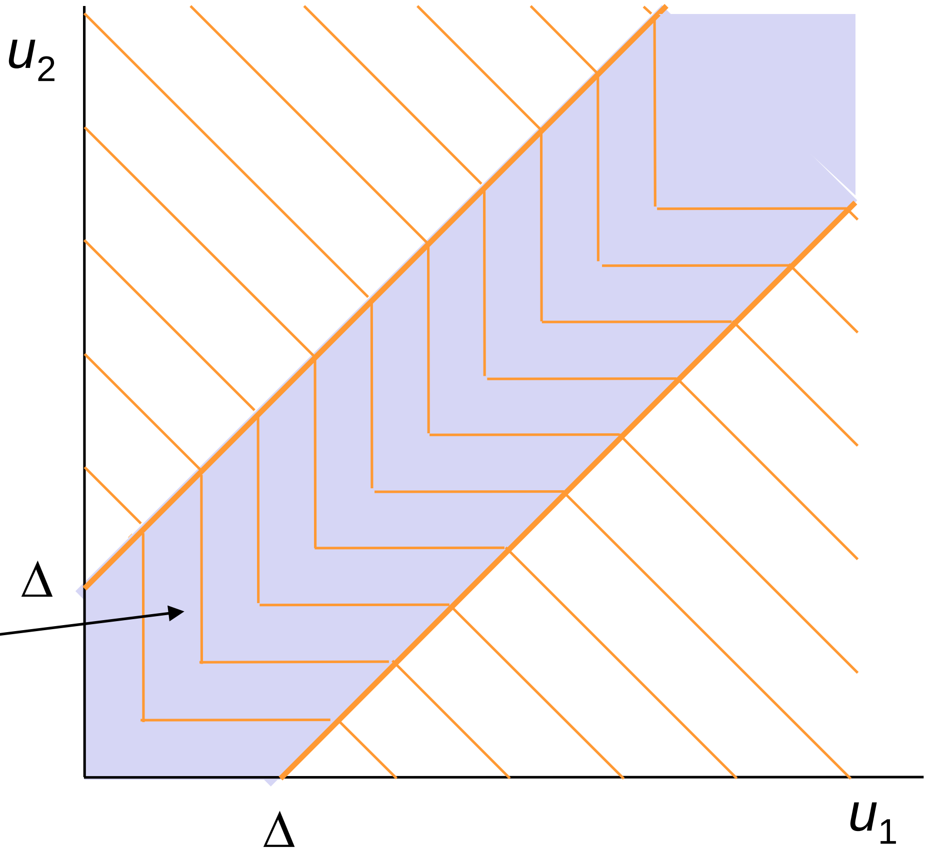


Rawlsian region

$\min\{u_1, u_2\}$

Two-person Model

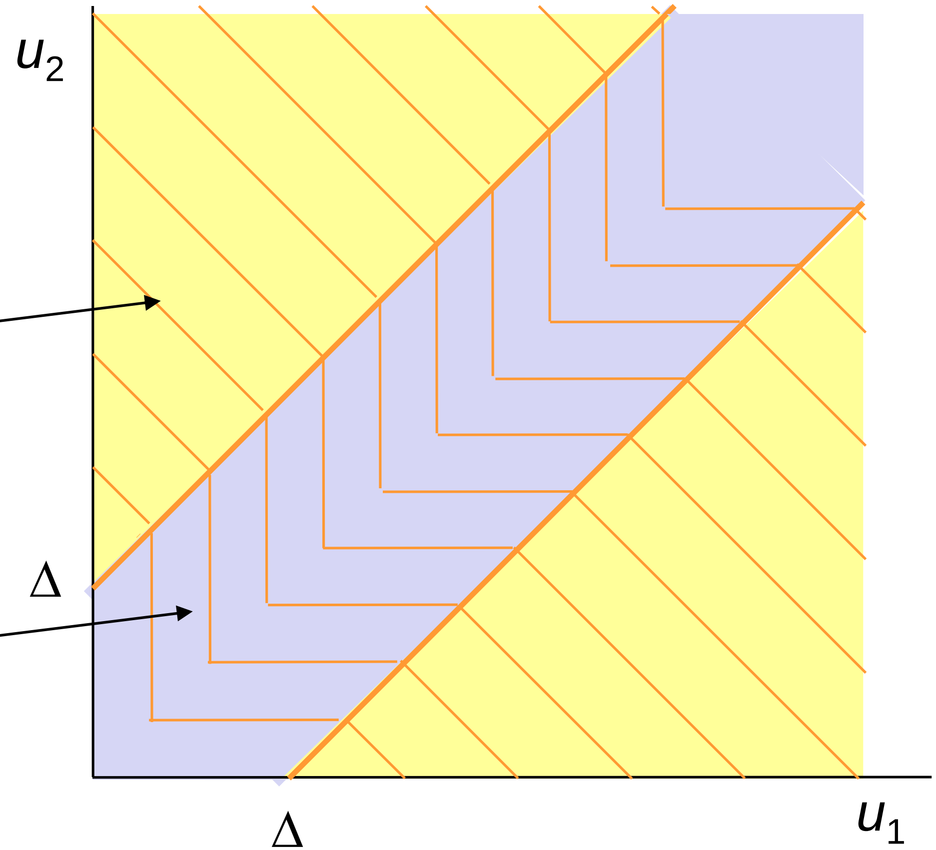
Contours of **social welfare function** for 2 persons.

Utilitarian region

$u_1 + u_2$

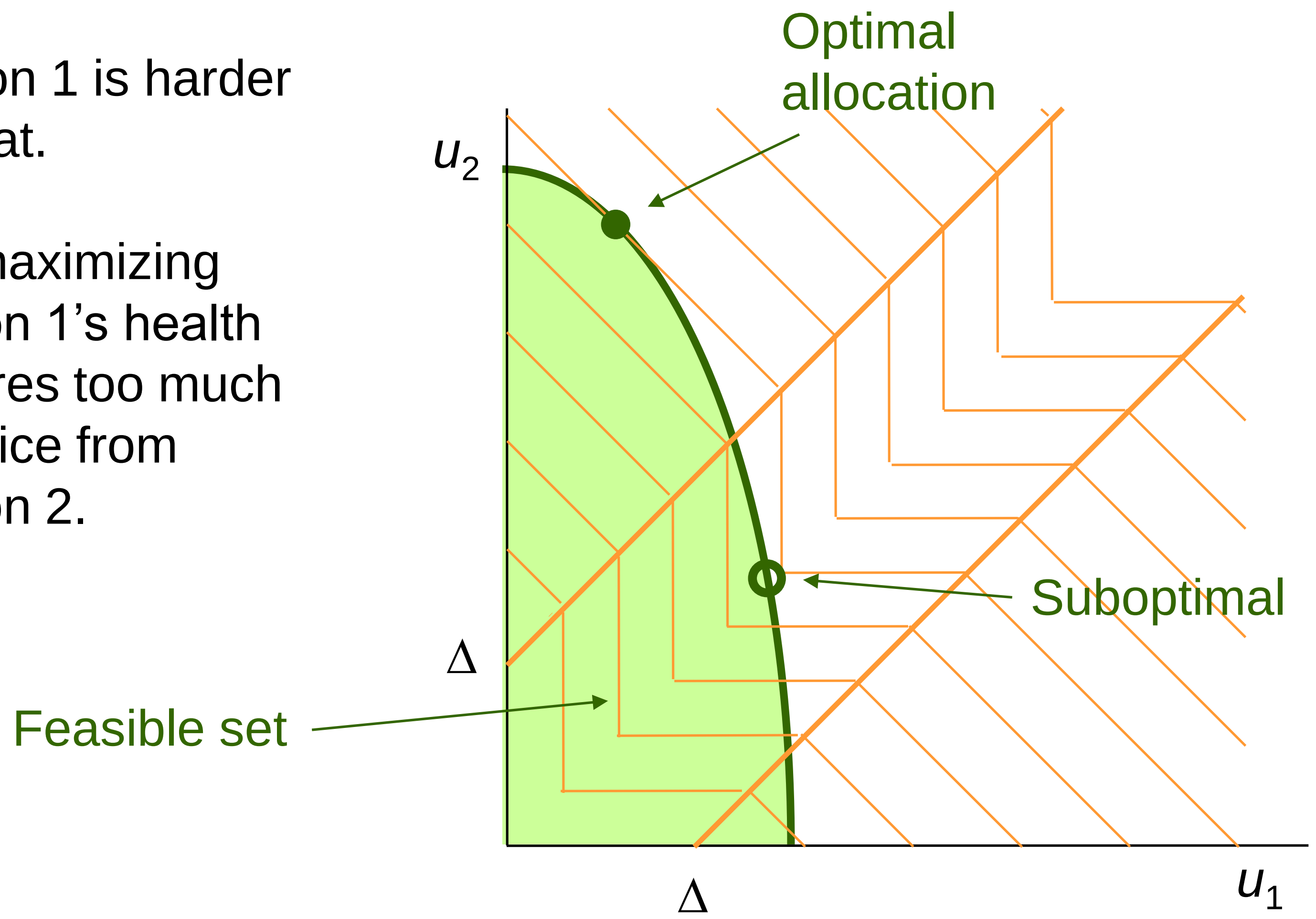
Rawlsian region

$\min\{u_1, u_2\}$



Person 1 is harder to treat.

But maximizing person 1's health requires too much sacrifice from person 2.

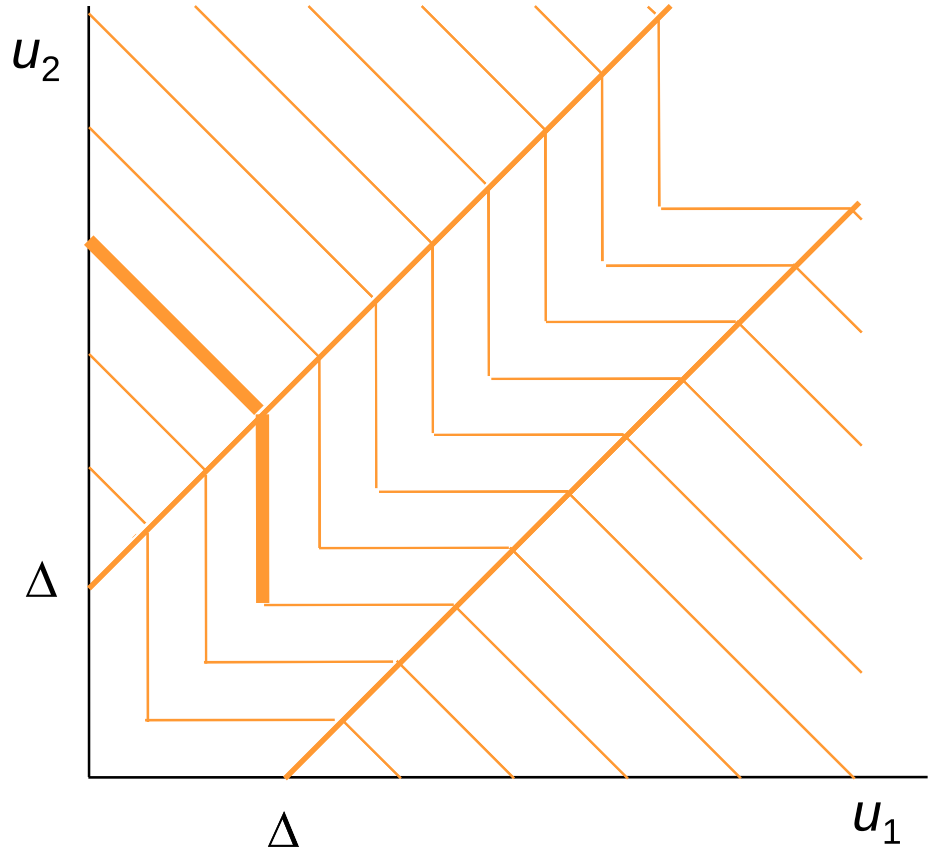


Advantages

- Only **one parameter** Δ
  - **Focus** for debate.
  - Δ has **intuitive meaning** (unlike weights)
  - Examine **consequences** of different settings for Δ
  - Find **least objectionable** setting
  - Results in a **consistent** policy

Social Welfare Function

We want continuous contours…

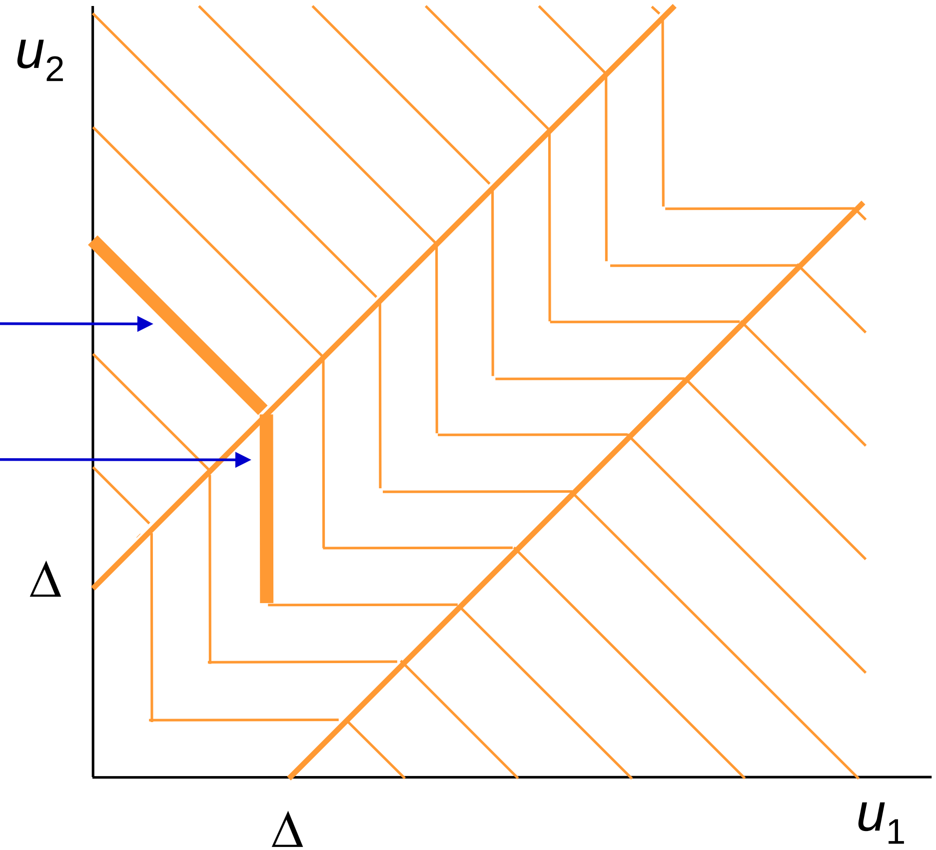


Social Welfare Function

We want continuous contours…

$u_1 + u_2$

$2\min\{u_1, u_2\} u_1 + \Delta$



So we use affine transform of Rawlsian criterion

Social Welfare Function

The social welfare problem becomes

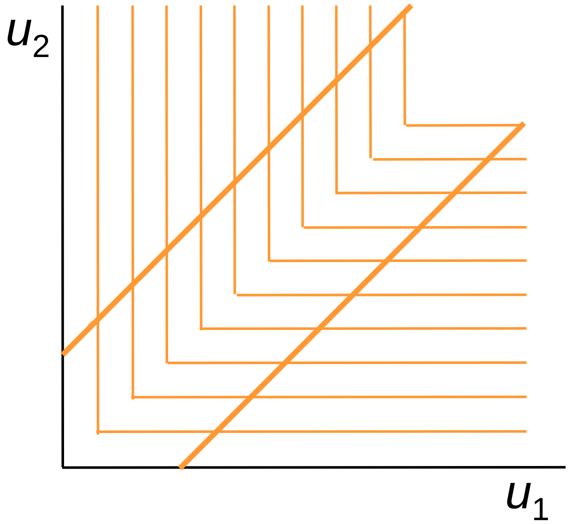
$$\max \; f(u_1, u_2)$$

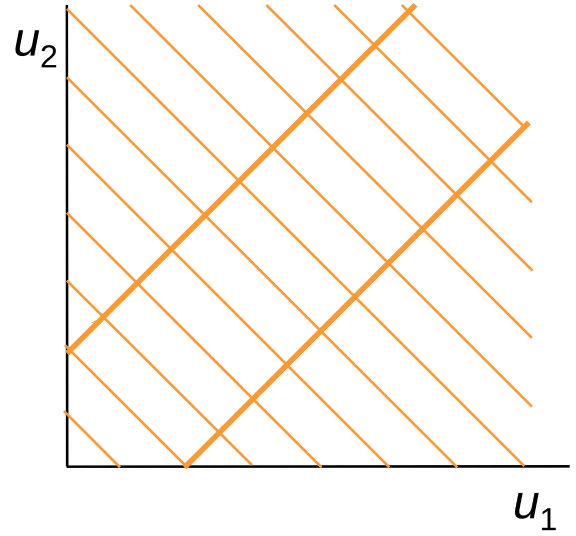
$$f(u_1, u_2) = \left\{ \begin{array}{ll} 2\min\{u_1, u_2\} + \Delta, & \text{if } |u_1 - u_2| \le \Delta \\ u_1 + u_2, & \text{otherwise} \end{array} \right\}$$

constraints on feasible set

MILP Model

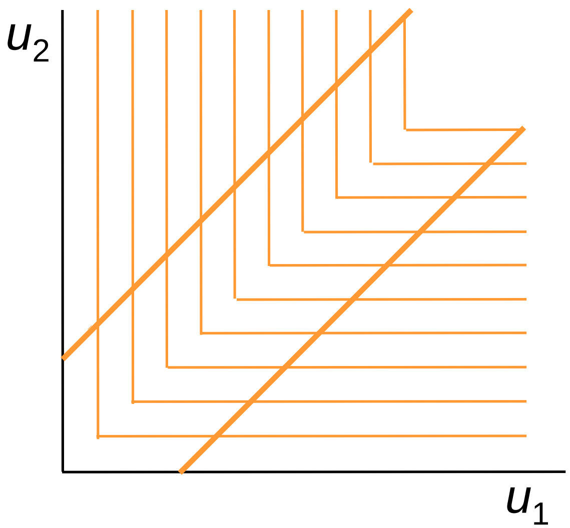
Hypograph (epigraph when minimizing) is union of 2 polyhedra.

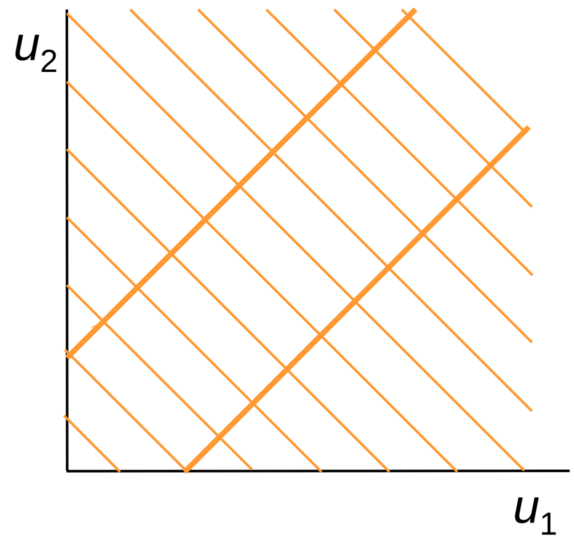




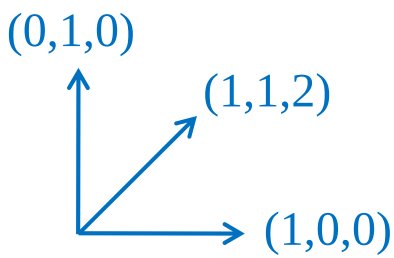
MILP Model

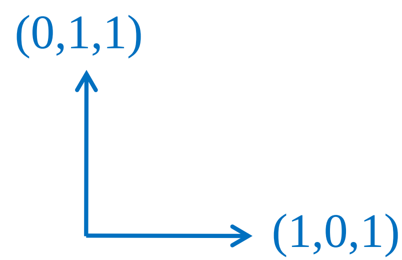
Epigraph is union of 2 polyhedra.
Because they have **different recession cones**, there is no MILP model.





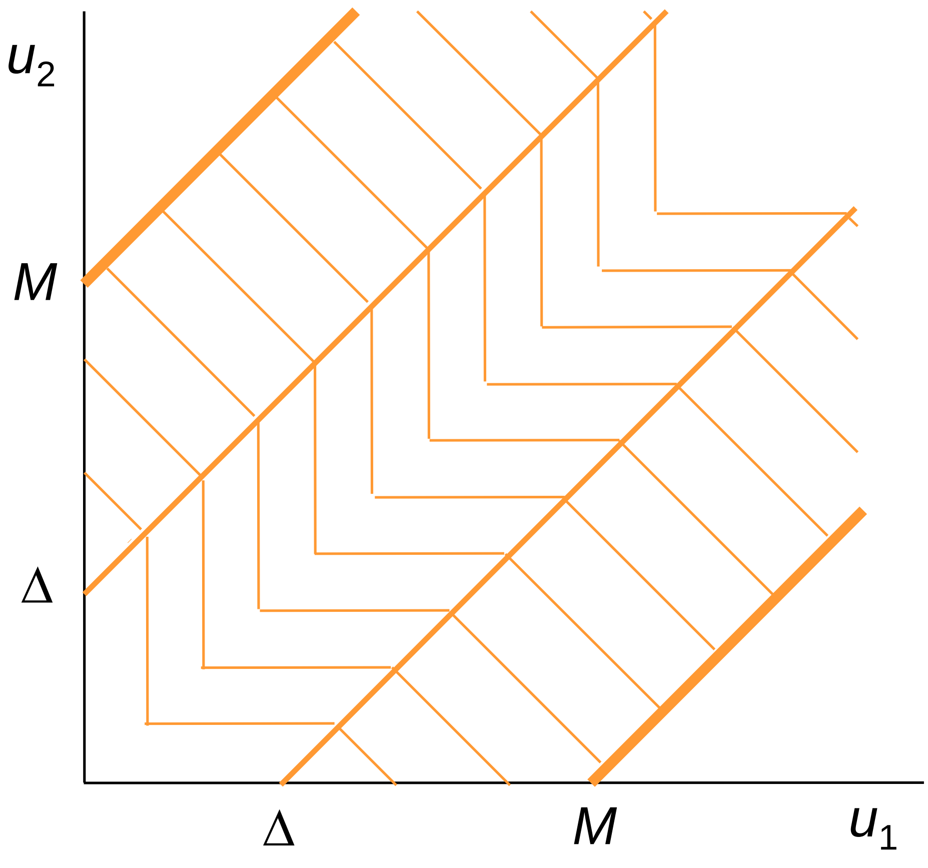
Recession directions (u_1,u_2,z)





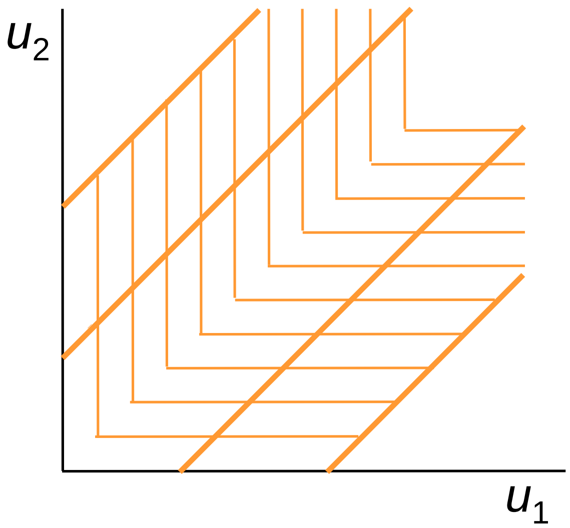
MILP Model

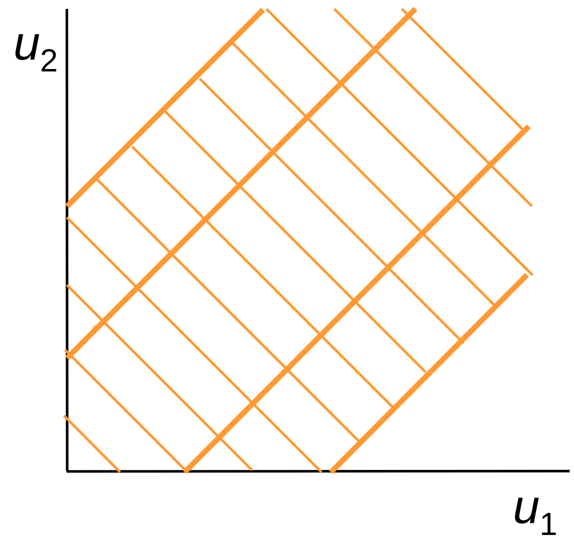
Impose constraints $|u_1 - u_2| \leq M$



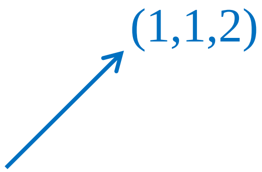
MILP Model

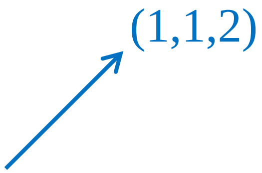
This equalizes recession cones.





Recession directions (u_1,u_2,z)





MILP Model

We have the model…

$$\max\ z$$

$$z \le 2u_i + \Delta + (M-\Delta)\delta, \quad i = 1,2$$

$$z \le u_1 + u_2 + \Delta(1-\delta)$$

$$u_1 - u_2 \le M, \quad u_2 - u_1 \le M$$

$$u_1, u_2 \ge 0$$

$$\delta \in \{0,1\}$$

constraints on feasible set

u_1

MILP Model

We have the model…

$$
\begin{aligned}
&\max\ z \\
&z \le 2u_i + \Delta + (M - \Delta)\delta, \quad i = 1,2 \\
&z \le u_1 + u_2 + \Delta(1-\delta) \\
&u_1 - u_2 \le M, \quad u_2 - u_1 \le M \\
&u_1, u_2 \ge 0 \\
&\delta \in \{0,1\}
\end{aligned}
$$

This is a **convex hull** formulation.

n-person Model

Rewrite the 2-person **social welfare function** as…

$$f(u_1,u_2)=\Delta+2u_{\min}+\left(u_1-u_{\min}-\Delta\right)^+ +\left(u_2-u_{\min}-\Delta\right)^+$$

$\min\{u_1,u_2\}$

$\alpha^+ = \max\{0,\alpha\}$

n-person Model

Rewrite the 2-person **social welfare function** as…

$$f(u_1, u_2) = \Delta + 2u_{\min} + (u_1 - u_{\min} - \Delta)^+ + (u_2 - u_{\min} - \Delta)^+$$

$\min\{u_1, u_2\}$

$\alpha^+ = \max\{0, \alpha\}$

This can be generalized to *n* persons:

$$f(u) = (n-1)\Delta + nu_{\min} + \sum_{j=1}^{n} (u_1 - u_{\min} - \Delta)^+$$

n-person Model

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$$f(u_1,u_2) = \Delta + 2u_{\min} + \left(u_1 - u_{\min} - \Delta\right)^+ + \left(u_2 - u_{\min} - \Delta\right)^+$$

$\min\{u_1,u_2\}$

$\alpha^+ = \max\{0,\alpha\}$

This can be generalized to *n* persons:

$$f(u) = (n-1)\Delta + nu_{\min} + \sum_{j=1}^{n}\left(u_1 - u_{\min} - \Delta\right)^+$$

Epigraph is a union of $n!$ polyhedra with same recession direction $(u,z) = (1,\ldots,1,n)$ if we require $|u_i - u_j| \le M$

So there is an MILP model…

n-person MILP Model

To avoid $n!$ 0-1 variables, add auxiliary variables w_{ij}

$$
\begin{aligned}
&\max\ z \\
&z \le u_i + \sum_{j \ne i} w_{ij},\ \text{all } i \\
&w_{ij} \le \Delta + u_i + \delta_{ij}(M - \Delta),\ \text{all } i, j \text{ with } i \ne j \\
&w_{ij} \le u_j + (1 - \delta_{ij})\Delta,\ \text{all } i, j \text{ with } i \ne j \\
&u_i - u_j \le M,\ \text{all } i, j \\
&u_i \ge 0,\ \text{all } i \\
&\delta_{ij} \in \{0,1\},\ \text{all } i, j \text{ with } i \ne j
\end{aligned}
$$

n-person MILP Model

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&\max\ z \\
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&u_i - u_j \le M,\ \text{all } i,j \\
&u_i \ge 0,\ \text{all } i \\
&\delta_{ij} \in \{0,1\},\ \text{all } i,j \text{ with } i \ne j
\end{aligned}
$$

u_1

Theorem. The model is correct (not easy to prove).

n-person MILP Model

To avoid $n!$ 0-1 variables, add auxiliary variables w_{ij}

$$\max\ z$$

$$z \le u_i + \sum_{j \ne i} w_{ij},\ \text{ all } i$$

$$w_{ij} \le \Delta + u_i + \delta_{ij}(M - \Delta),\ \text{ all } i, j \text{ with } i \ne j$$

$$w_{ij} \le u_j + (1 - \delta_{ij})\Delta,\ \text{ all } i, j \text{ with } i \ne j$$

$$u_i - u_j \le M,\ \text{ all } i, j$$

$$u_i \ge 0,\ \text{ all } i$$

u_1

$$\delta_{ij} \in \{0,1\},\ \text{ all } i, j \text{ with } i \ne j$$

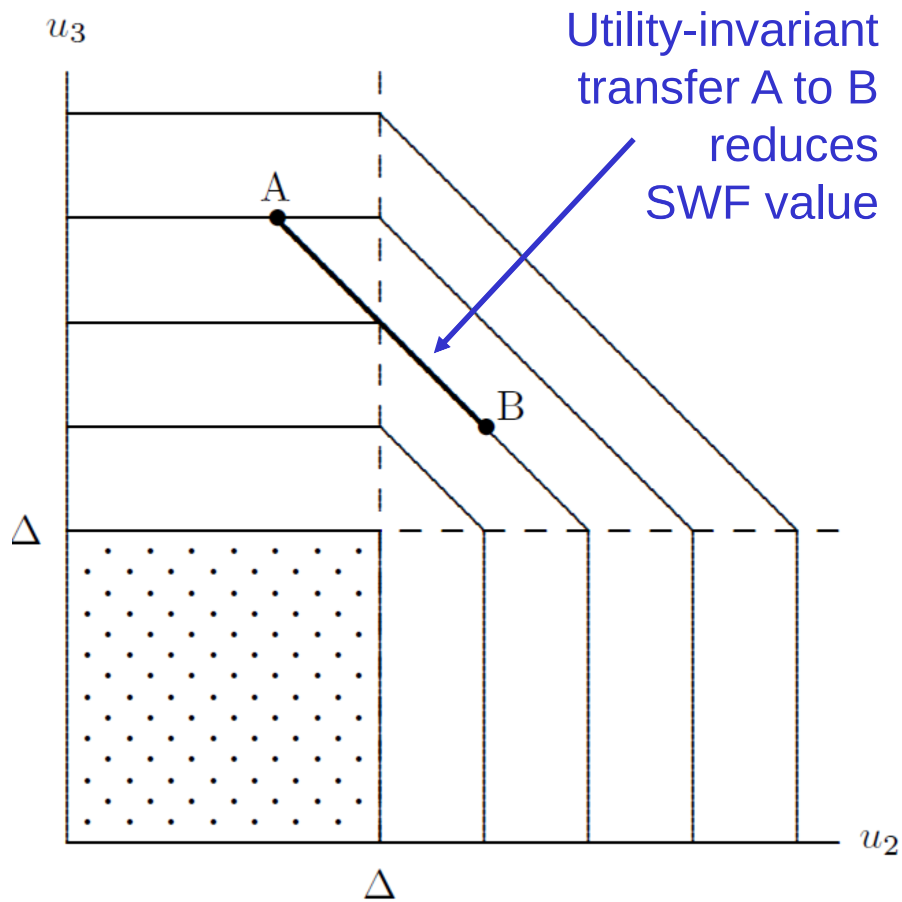
Theorem. The model is correct (not easy to prove).

Theorem. This is a convex hull formulation (not easy to prove).

Pigou-Dalton Condition

The SWF satisfies Pigou-Dalton for n = 2 but **not** for $n \geq 3$.

But it satisfies a slightly weaker Cheateauneuf-Moyes condition.



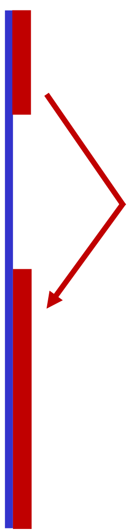
Assume $u_1 = 0$

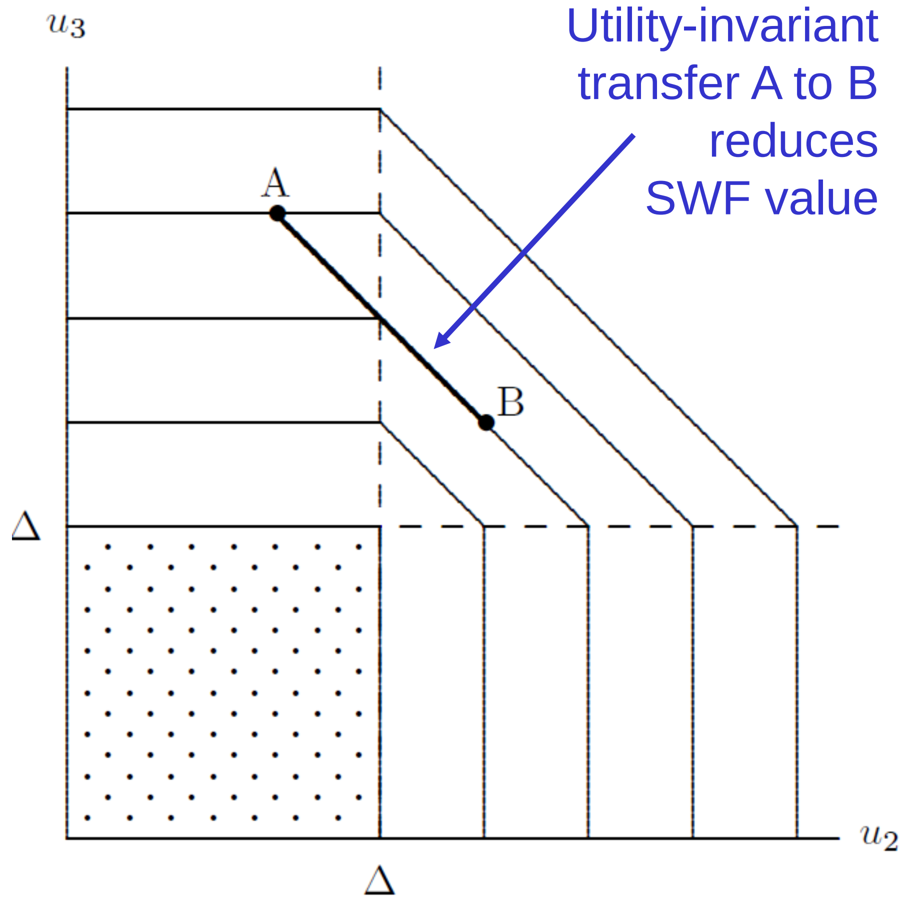
Pigou-Dalton Condition

The SWF satisfies Pigou-Dalton for n = 2 but **not** for $n \geq 3$.

But it satisfies a slightly weaker Cheateauneuf-Moyes condition.

It examines transfers from people at the top (all sacrificing equally) to people at the bottom (all benefiting equally)





Assume $u_1 = 0$

n-group Model

In practice, funds may be allocated to groups of different sizes

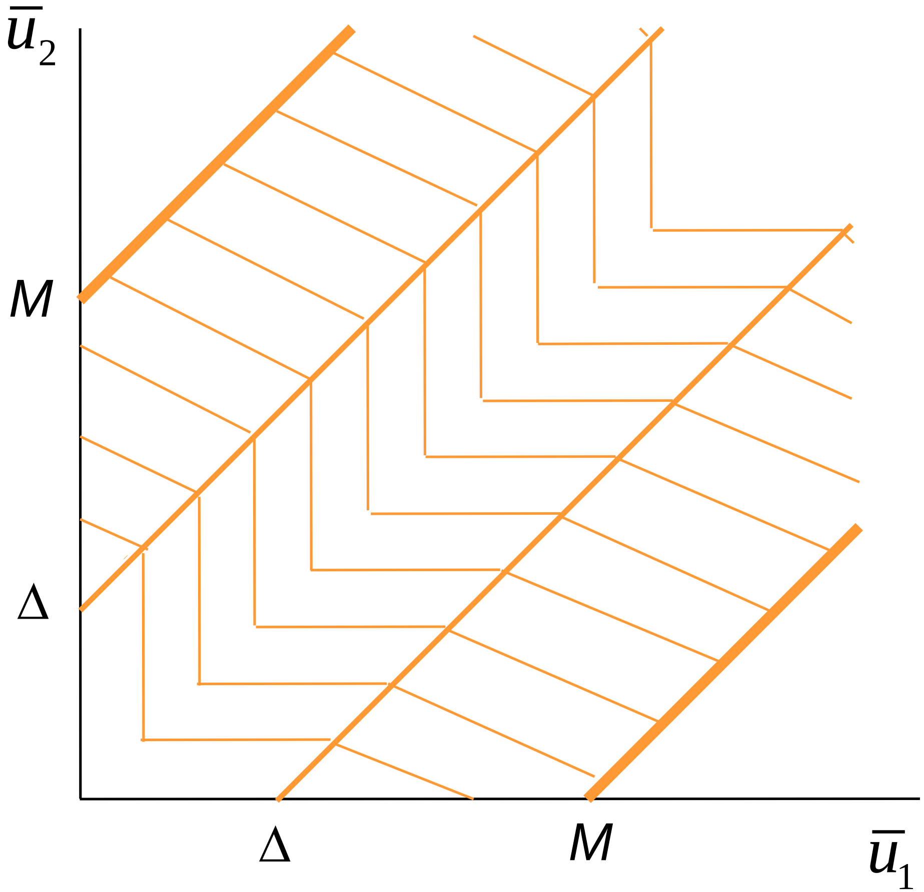
For example, disease/treatment categories.

Let $\bar{u}_i$ = average utility gained by a person in group *i*

n_i = size of group *i*

n-group Model

2-person case with $n_1 < n_2$. Contours have slope $= n_1/n_2$



n-group MILP Model

Again add auxiliary variables w_{ij}

$$
\begin{aligned}
&\max\ z \\
&z \le (n_i - 1)\Delta + n_i \bar{u}_i + \sum_{j \ne i} w_{ij}, \ \text{all } i \\
&w_{ij} \le n_j(\bar{u}_i + \Delta) + \delta_{ij} n_j (M - \Delta), \ \text{all } i,j \text{ with } i \ne j \\
&w_{ij} \le \bar{u}_j + (1 - \delta_{ij}) n_j \Delta, \ \text{all } i,j \text{ with } i \ne j \\
&\bar{u}_i - \bar{u}_j \le M, \text{ all } i,j \\
&\bar{u}_i \ge 0, \text{ all } i \\
&\delta_{ij} \in \{0,1\}, \ \text{all } i,j \text{ with } i \ne j
\end{aligned}
$$

u_1

Theorem. The model is correct.

Theorem. This is a convex hull formulation.

Health Example

Measure utility in QALYs (quality-adjusted life years).

QALY and cost data based on Briggs & Gray, (2000) etc.

Each group is a disease/treatment pair.

Treatments are discrete, so group funding is all-or-nothing.

Divide groups into relatively homogeneous subgroups.

u_1

Health Example

Add constraints to define feasible set…

$$\max\ z$$

$$z \le (n_i - 1)\Delta + n_i \bar{u}_i + \sum_{j \ne i} w_{ij},\ \text{all } i$$

$$w_{ij} \le n_j(\bar{u}_i + \Delta) + \delta_{ij} n_j (M - \Delta),\ \text{all } i,j \text{ with } i \ne j$$

$$w_{ij} \le \bar{u}_j + (1 - \delta_{ij}) n_j \Delta,\ \text{all } i,j \text{ with } i \ne j$$

$$\bar{u}_i - \bar{u}_j \le M, \text{ all } i,j$$

$$\bar{u}_i \ge 0, \text{ all } i$$

$$\delta_{ij} \in \{0,1\},\ \text{all } i,j \text{ with } i \ne j$$

$$u_1$$

$$\boxed{\begin{aligned} &\bar{u}_i = q_i y_i + \alpha_i \\ &\sum_i n_i c_i y_i \le \text{budget} \\ &y_i \in \{0,1\},\ \text{all } i \end{aligned}}$$

y_i indicates whether subgroup *i* is funded

QALY & cost data

Part 1

Intervention	Cost per person c_i (£)	QALYs gained q_i	Cost per QALY (£)	QALYs without intervention α_i	Subgroup size n_i
Pacemaker for atrioventricular heart block					
Subgroup A	3500	3	1167	13	35
Subgroup B	3500	5	700	10	45
Subgroup C	3500	10	350	5	35
Hip replacement					
Subgroup A	3000	2	1500	3	45
Subgroup B	3000	4	750	4	45
Subgroup C	3000	8	375	5	45
Valve replacement for aortic stenosis					
Subgroup A	4500	3	1500	2.5	20
Subgroup B	4500	5	900	3	20
Subgroup C	4500	10	450	3.5	20
CABG[1] for left main disease					
Mild angina	3000	1.25	2400	4.75	50
Moderate angina	3000	2.25	1333	3.75	55
Severe angina	3000	2.75	1091	3.25	60
CABG for triple vessel disease					
Mild angina	3000	0.5	6000	5.5	50
Moderate angina	3000	1.25	2400	4.75	55
Severe angina	3000	2.25	1333	3.75	60
CABG for double vessel disease					
Mild angina	3000	0.25	12,000	5.75	60
Moderate angina	3000	0.75	4000	5.25	65
Severe angina	3000	1.25	2400	4.75	70

QALY & cost data

Part 2

Intervention	Cost per person c_i (£)	QALYs gained q_i	Cost per QALY (£)	QALYs without intervention α_i	Subgroup size n_i
	22,500	4.5	5000	1.1	2
Kidney transplant					
Subgroup A	15,000	4	3750	1	8
Subgroup B	15,000	6	2500	1	8
Kidney dialysis					
Less than 1 year survival					
Subgroup A	5000	0.1	50,000	0.3	8
1-2 years survival					
Subgroup B	12,000	0.4	30,000	0.6	6
2-5 years survival					
Subgroup C	20,000	1.2	16,667	0.5	4
Subgroup D	28,000	1.7	16,471	0.7	4
Subgroup E	36,000	2.3	15,652	0.8	4
5-10 years survival					
Subgroup F	46,000	3.3	13,939	0.6	3
Subgroup G	56,000	3.9	14,359	0.8	2
Subgroup H	66,000	4.7	14,043	0.9	2
Subgroup I	77,000	5.4	14,259	1.1	2
At least 10 years survival					
Subgroup J	88,000	6.5	13,538	0.9	2
Subgroup K	100,000	7.4	13,514	1.0	1
Subgroup L	111,000	8.2	13,537	1.2	1

Results

Total budget £3 million

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	Kidney dialysis 1-2	Kidney dialysis 2-5	Kidney dialysis 5-10	Kidney dialysis > 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Utilitarian solution

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	Kidney dialysis 1-2	Kidney dialysis 2-5	Kidney dialysis 5-10	Kidney dialysis > 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Rawlsian solution

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	1-2	2-5	5-10	> 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Fund for all Δ

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	Kidney dialysis 1-2	Kidney dialysis 2-5	Kidney dialysis 5-10	Kidney dialysis > 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

More dialysis with larger Δ, beginning with longer life span

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	Kidney dialysis 1-2	Kidney dialysis 2-5	Kidney dialysis 5-10	Kidney dialysis > 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Abrupt change at Δ = 5.60

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	1-2	2-5	5-10	> 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Come and go together

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	1-2	2-5	5-10	> 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

In-out-in

Δ	Pace-	Hip	Aortic	CABG			Heart	Kidney	Kidney dialysis				
range	maker	repl.	valve	L	3	2	trans.	trans.	< 1	1-2	2-5	5-10	> 10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Results

Most rapid change. Possible range for politically acceptable compromise

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis <1	1-2	2-5	5-10	>10
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111

Puzzle

Curious fact: Rawlsian solution ($\Delta = \infty$) achieves greater utility than some smaller values of Δ.
Why?

Δ range	Pace-maker	Hip repl.	Aortic valve	CABG L	CABG 3	CABG 2	Heart trans.	Kidney trans.	Kidney dialysis < 1	Kidney dialysis 1-2	Kidney dialysis 2-5	Kidney dialysis 5-10	Kidney dialysis > 10	Avg. QALYs
0–3.3	111	111	111	111	111	111	1	11	0	0	000	0000	000	7.54
3.4–4.0	111	111	111	111	111	111	0	11	1	0	000	0000	000	7.54
4.0–4.4	111	111	111	111	111	111	0	01	1	0	000	0000	001	7.51
4.5–5.01	111	011	111	111	111	111	1	01	1	0	000	0000	011	7.43
5.02–5.55	111	011	011	111	111	111	0	01	1	0	000	0001	011	7.36
5.56–5.58	111	011	011	111	111	011	0	01	1	0	000	0001	111	7.36
5.59	111	011	011	110	111	111	0	01	1	0	000	0001	111	7.20
5.60–13.1	111	111	111	101	000	000	1	11	1	0	111	1111	111	7.06
13.2–14.2	111	011	111	011	000	000	1	11	1	1	111	1111	111	7.03
14.3–15.4	111	111	111	011	000	000	1	11	1	1	101	1111	111	7.13
15.5–up	111	011	111	011	001	000	1	11	1	0	011	1111	111	7.19

Puzzle

Curious fact: Rawlsian solution ($\Delta = \infty$) achieves greater utility than some smaller values of Δ.
Why?

Rawlsian solution cares only about the **very worst-off** (i.e., most serious category of kidney disease).

The MILP breaks ties by adding $\varepsilon \cdot \text{utility}$ to SWF.

Utility is a larger factor when $\Delta = \infty$ than for smaller values of Δ.

Puzzle

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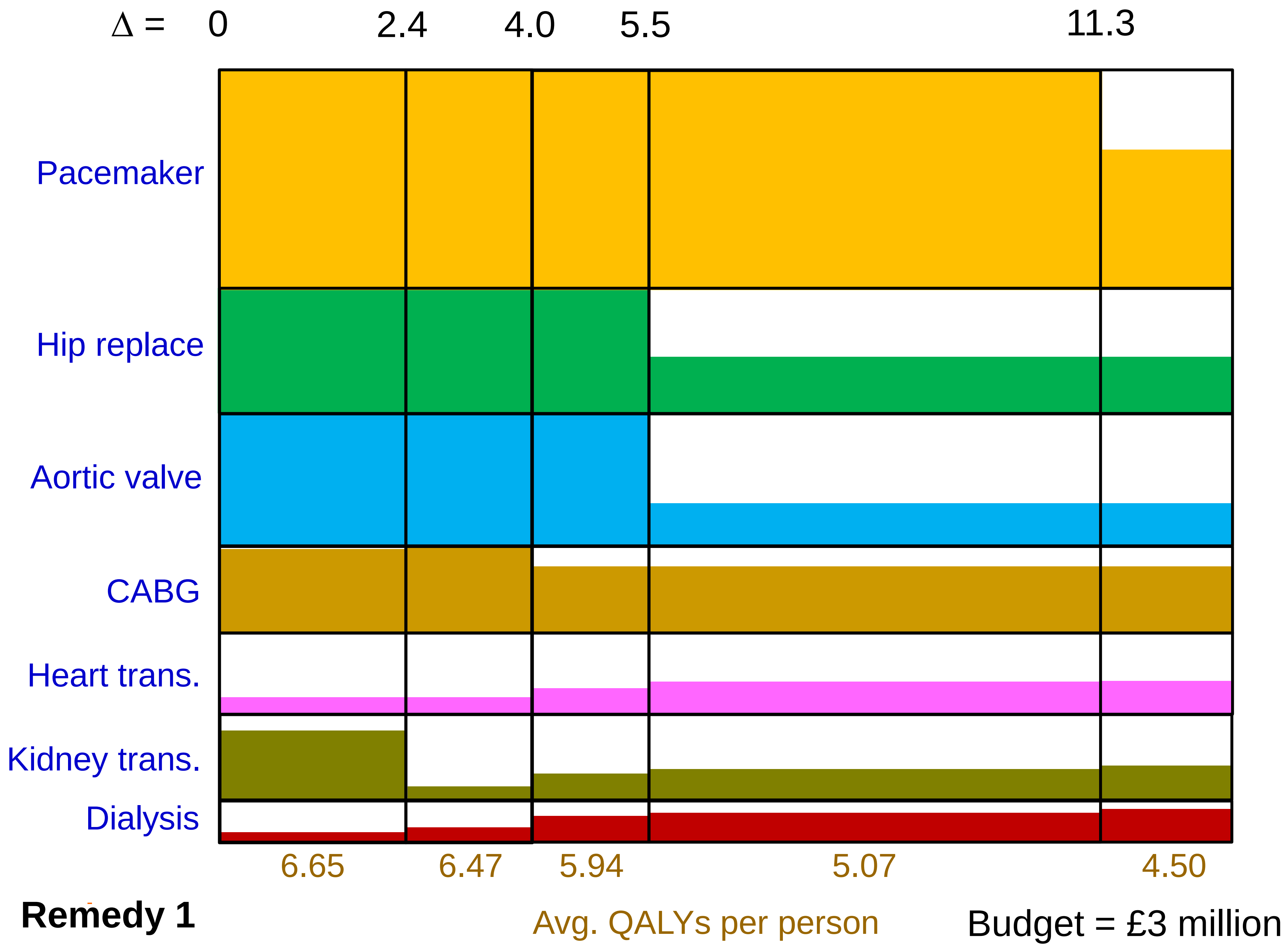
The MILP breaks ties by adding $\varepsilon \cdot$ utility to SWF.

Utility is a larger factor when $\Delta = \infty$ than for smaller values of Δ.

Remedy 1. View each disease as a single group with concave utility function (decreasing marginal utility)

Remedy 2. Design a SWF that combines **leximax** (rather than maximin) with utility



Δ = 0
2.4
4.0
5.5
11.3
Pacemaker
Hip replace
Aortic valve
CABG
Heart trans.
Kidney trans.
Dialysis
6.65
6.47
5.94
5.07
4.50
Remedy 1
Avg. QALYs per person
Budget = £3 million

Remedy 1

Problem: This doesn't address fairness **within** disease categories (more serious vs. less serious cases).

Remedy 2

Design a SWF to **combine leximax and utility.**

Rather than maximize one function, compute

$$\text{leximax}\big(F_1(u),\ldots,F_n(u)\big)$$

where

$$F_k(u) = \begin{cases} \displaystyle\sum_{i=1}^{k} u_{\langle i\rangle} + \big(t(u)-k\big)\big(u_{\langle 1\rangle}+\Delta\big) + \sum_{i=t(u)+1}^{n} u_{\langle i\rangle} & \text{for } k < t(u) \\ \displaystyle\sum_{i=1}^{n} u_{\langle i\rangle} & \text{for } k \geq t(u) \end{cases}$$

and $u_{\langle i\rangle}$ is i-th smallest of $u_1,\ldots,u_n$

and $u_{\langle k\rangle} - u_{\langle 1\rangle} \leq \Delta$ for $k = 1,\ldots,t(u)$

Remedy 2

Each $F_k(u)$ is continuous and satisfies the Chateauneuf-Moyes condition.

How to model it in an MILP?

Ongoing research…

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Questions/Discussion