Social and Information Networks

University of Toronto CSC303
Winter/Spring 2023

Week 9: March 13-17

This week's agenda

- Mitochondrial Eve
  - Problem setup (Ch 21.7)
  - Wright-Fisher single-parent ancestry model (Ch 21.7)
  - Estimation of time to convergence (Ch 21.8B)
- Bargaining in a Network Exchange Model
  - Power in the network exchange social experiment (Ch 12.1-12.3)
  - Stable outcomes (Ch 12.7)
  - The Ultimatum Game (Ch 12.6)
  - Balanced outcomes (Ch 12.5, 12.8)

Genetic inheritance and networks

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  - This woman is called **Mitochondrial Eve**
  - She lived sometime between 100,000 and 200,000 years ago
  - Probably living in Africa
- We'll ignores the issue of the location of Mitochondrial Eve and focuses on the basis (i.e. a model based on various assumptions) for this bold assertion of a common ancestry

Note: I suggest reading the text as to the caveats about the model (see Ch 21.7)

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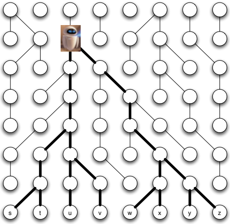
Mitochondrial Eve continued

- Focussing on mitochondrial DNA, and assuming pure inheritance from the mother, then we can consider a "single parent" ancestry model



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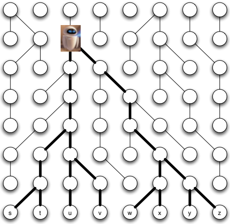

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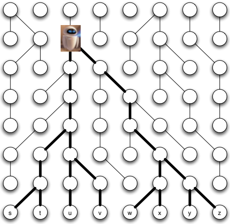

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- This does **not** say that Mitochondrial Eve was the only woman alive at this time, but that our mitochondrial DNA traces back to one woman
- Additionally, our genomic makeup does come from both parents

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  - assume a fixed population of N individuals throughout the entire period of time
- Problems? Obviously inconsistent with the fact that world population is growing
- Ultimately does not change the nature of the conclusions or even the nature of the analysis
  - In fact, once we accept that populations are growing, it is clear that certain individuals must be having multiple children which is also part of the model

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- Each individual at time t+1 has its "single parent" chosen uniformly at random from the previous generation
  - A significant assumption given geography, ethnicity, etc...
  - To reconcile this (with respect to the assertion of a single Mitochondrial Eve), we need to understand the extent to which individual communities can be isolated
    - ★ Ultimately, the timing for when common ancestry would have taken place is not impacted by this assumption

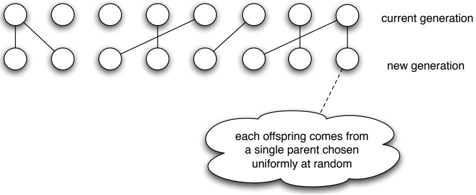
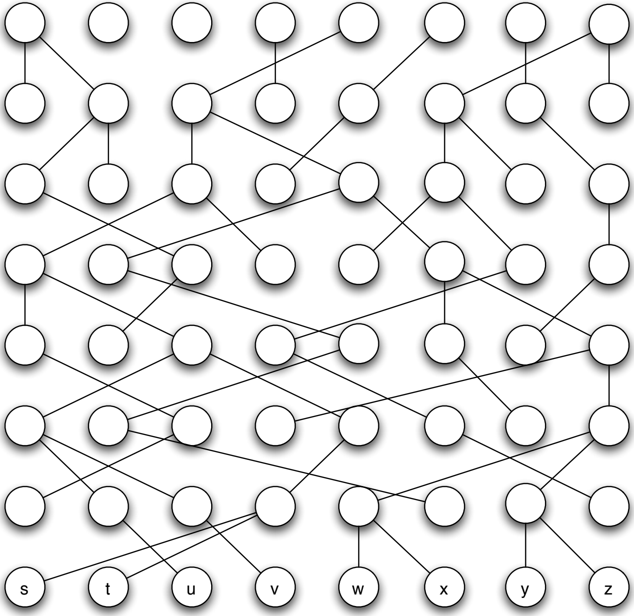
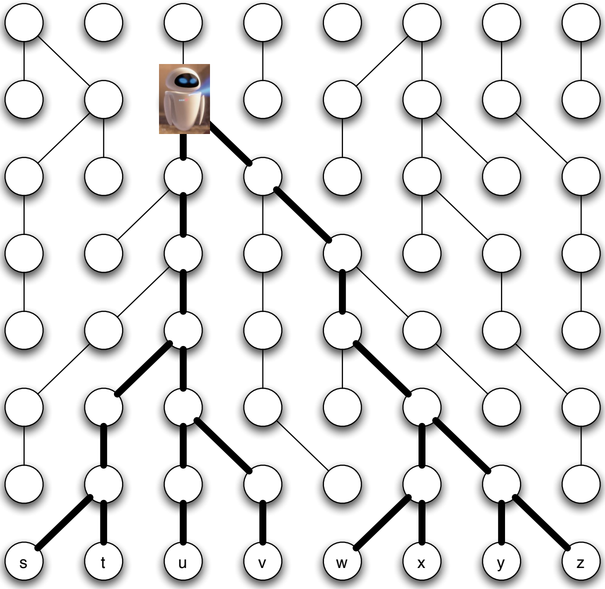


Figure: [Fig 21.11, E&K]

More generations of the model



Ancestry depicted.



The analysis for estimating the time that the model coalesces on Mitochondrial Eve

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Suppose we have a total population of N and at some point of time $t+1$ that we are down to k candidates (lineages) for a common ancestor. We want to consider the probability that two lineages will collide so that there be (at most) $k-1$ candidates.

Wed. Mar 15th: Announcements & Corrections

- No in-person office hours today; I might be unable to attend the online office hour either :(
  - I'm still available by appointment, and Piazza
- Assignment 2 is due in a week (March 23rd)
- Draft of critical review due in a week (March 24th)
  - The peer review software is being set up, instructions should be up soon(TM)

The analysis

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Case: $k = 2$. Say the active lineage is individuals $\{a, b\}$. Then the probability that b does not share a's parent is $1 - \frac{1}{N}$.

Case: $k > 2$. Lets consider the probability that none of the k nodes share a parent. There will be no collapsing if the second node doesn't collide with the first, the third doesn't collide with the first two, etc, so this means that the probability of no collapsing is :

$$(1 - \frac{1}{N})(1 - \frac{2}{N}) \cdots (1 - \frac{k-1}{N})$$

The analysis continued

The previous product

$$(1-\frac{1}{N})(1-\frac{2}{N})\cdots(1-\frac{k-1}{N})$$

is at most:

$$1-\left(\frac{1+2+\cdots+k-1}{N}\right)+\frac{g(k)}{N^2}$$

where $g(k)$ depends only on k and not on N.

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where $g(k)$ depends only on k and not on N.

For any fixed k, the latter term is relatively negligible and we can say that the probability that none of the k share a parent is $1-\frac{k(k-1)}{2N}$.

The analysis continued

Fact: If we have a binary random variable Y_k (i.e., a heads coin flip) that is true with probability p, then the expected number of independent samples until Y_k is true (denoted $E[X_k]$) is exactly $1/p$

- if the probability is at least p, then the expected time can only be shorter.

Look familiar?

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Therefore, letting X_k denote the time to collapse from k to less than k lineages, then $E[X_k]$ is approximated by $\frac{2N}{k(k-1)}$

Note: Initially when k is large, the decrease is expected every generation going back. But when k is a small constant, then the expected number of generations to show a decrease is proportional to N.

Depiction of the lineages colliding

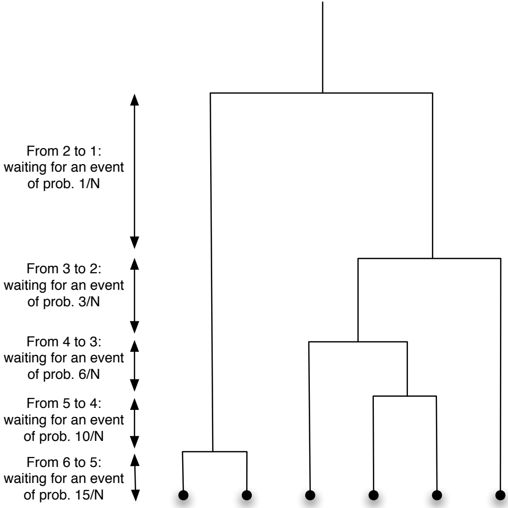

Figure: Assuming no three lineages collide simultaneously. [Fig 21.1(a), E&K]

Finishing the analysis

Let $X^k = X_k + X_{k-1} + \cdots + X_2$ be the number of generation to reach a common ancestor starting from a lineage of k individuals.

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Since $\mathbb{E}[X_j] = \frac{2N}{j(j-1)}$ and $\frac{1}{j(j-1)} = \frac{1}{j-1} - \frac{1}{j}$, by linearity of expectations we have:

$$\begin{aligned}\mathbb{E}[X^k] &= \sum_{j=1}^{k} \frac{2N}{j(j-1)} \\ &= 2N\left(\left[\frac{1}{1} - \frac{1}{2}\right] + \left[\frac{1}{2} - \frac{1}{3}\right] + \cdots + \left[\frac{1}{k-1} - \frac{1}{k}\right]\right) \\ &= 2N\left(1 - \frac{1}{k}\right)\end{aligned}$$

Note: Further more detailed analysis is consistent with the basic analysis that was presented in the text.

Recap

- Mitochondrial Eve
  - Problem setup (Ch 21.7)
  - Wright-Fisher single-parent ancestry model (Ch 21.7)
  - Estimation of time to convergence (Ch 21.8B)

Chapter 12: Bargaining and Power in Networks

- We begin a subtle and fascinating topic: how individuals in a network come to agreement on an outcome!
  - Part of a larger subject called cooperative game theory and to some extent touches on behavioural game theory
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  - We have a course (CSC304) which covers game theory; as opposed to necessary minimum we'll be covering
- To ensure we're all on the same page, we'll informally mention some basic concepts to keep in mind
  - We've seen these concepts, at least implicitly, in the course material already :)

A few more comments on game theory concepts

- Individuals (agents) have strategies or actions and employ a (pure or mixed/randomized) strategy so as to act in self interest, always trying to maximize benefit or minimize cost

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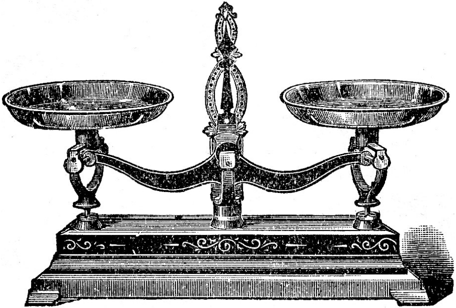
- Agents are acting in self interest implies that their actions are decentralized
  - *Mechanism design* concerns how a central agent can introduce incentives to influence agents
  - Aside: An example of a result in Mechanism Design is Gibbard-Satterthwaite theorem, which states that any voting rule is either
    - Dictatorial
    - Only selecting the winner from a set of two candidates
    - Susceptible to tactical voting

Game theory concepts: Equilibrium

Definition (Equilibrium)

A state in which no agent has an incentive to change their strategy assuming no one else is changing



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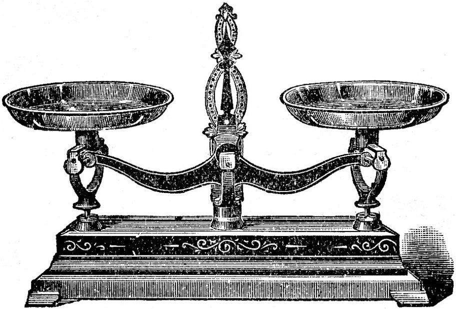

- Appeared in Schelling segregation model in Chapter 4, structural balance in Chapter 5, and will be important in Chapter 12 and the study of relative power
  - we will see them again in stable matchings and traffic equilibria

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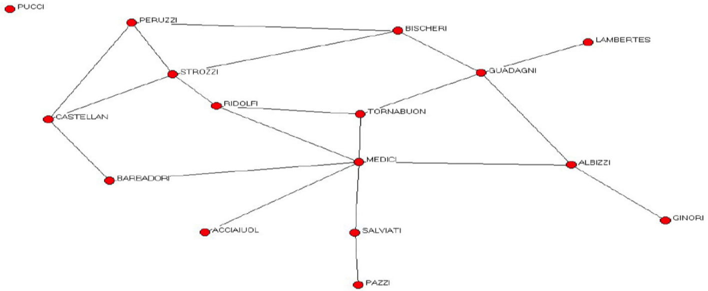

    - ★ In the first week we mentioned the network of Florentine marriages and how the *centrality* of the Medici family was said to have conferred power to the Medicis
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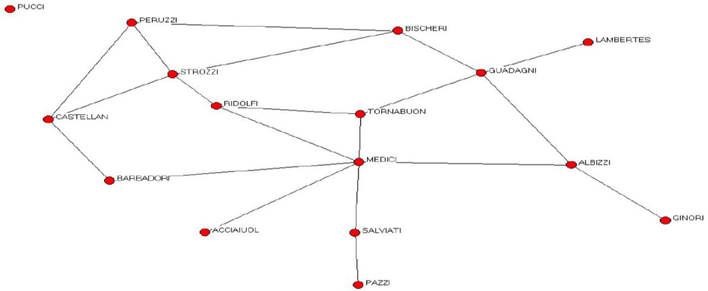

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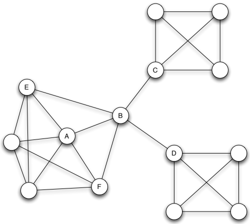
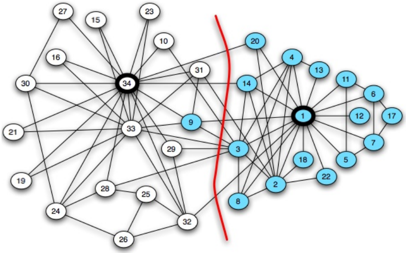
  - Second: The relative reputation, status, official position, exceptional attributes (intelligence, finances), etc...

Power: Bridging and bonding capital of nodes

The early chapters of the text provided some insights about the importance of centrality and bonding capital and bridging capital with regard to the *flow of information* and *trust*.





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- We will isolate power due to position in a network, and ignore the status aspects
- For motivation we begin with some illustrative network examples, we will follow this with a social experiment that will provide insight, and will in turn lead to precise definitions

Some illustrative examples

- Assume \$1 is placed on each edge of the network
  - each node trying to reach an agreement (within a fixed amount of time) on how to split the dollar
  - each node can only deal with at most one other adjacent node
    - In graph theoretic terms, this pairing of nodes is a *matching*: a subset of edges such that no node is adjacent to more than one edge in the matching

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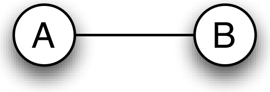

(a) *2-Node Path*

Does either party have an advantage?

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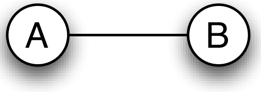
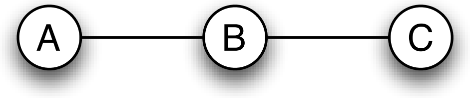


(a) *2-Node Path*

Does either party have an advantage?

No; a $\frac{1}{2} - \frac{1}{2}$ split is a reasonable predicted split that is observed in the experiments.

A three node path



(b) *3-Node Path*

What matching might occur and who each holds power?

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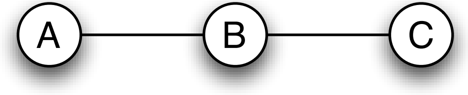

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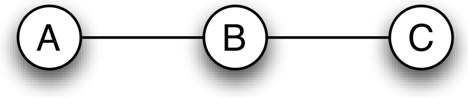
What matching might occur and who each holds power?

Clearly since we need a matching, either A and C will have to be left out. Intuitively then, node B holds much more power than A or C. The basic theory and experiments support this intuition.

What fraction of the \$ would you expect B to obtain in negotiating between A and C?

A three node path



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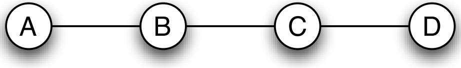
What matching might occur and who each holds power?

Clearly since we need a matching, either A and C will have to be left out. Intuitively then, node B holds much more power than A or C. The basic theory and experiments support this intuition.
What fraction of the $ would you expect B to obtain in negotiating between A and C?

There is a difference between the basic theory and the social experiments. In the experiments , B gets a $(\frac{5}{6})^{th}$ fraction of the $. The basic theory would predict that B gets all almost all of the $. Why the difference?

A four node path



(c) *4-Node Path*

What matching might occur and how might the money be split? Would B get more or less in this four node network than in the previous three node path?

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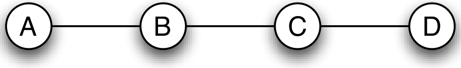

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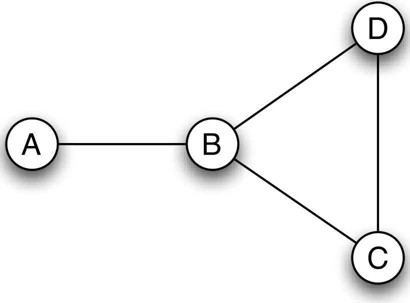
What matching might occur and how might the money be split? Would B get more or less in this four node network than in the previous three node path?

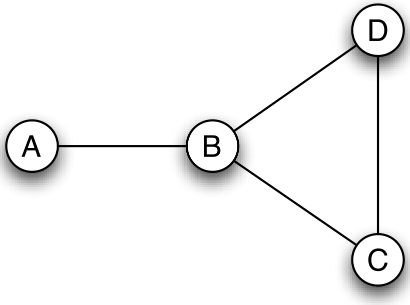
Here the experiments show that B gets a fraction of between $\frac{7}{12}^{th}$ and $\frac{2}{3}^{rd}$ of the \$, less than what we obtained in the three node network. Why?

The stem graph in figure 12.3



What matching might occur and how might the money be split? Would B get more or less in this stem network than in the previous three and four node paths?

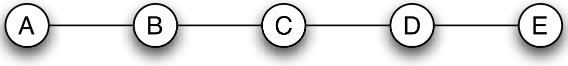
The stem graph in figure 12.3



What matching might occur and how might the money be split? Would B get more or less in this stem network than in the previous three and four node paths?

Experiments show that B in the stem graph makes slightly more money than B in the four node path (but less than in the three node path). Why?

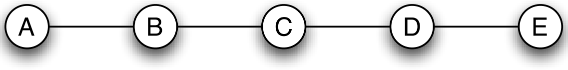
A five node path



(d) *5-Node Path*

Does C have any power (i.e. fraction of money obtained) compared to other nodes?

A five node path



(d) *5-Node Path*

Does C have any power (i.e. fraction of money obtained) compared to other nodes?

Intuitively B and D have most of the power in the five node path network. The text states that in experiments, C has slightly more power than A or E.

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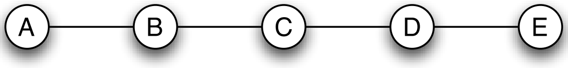


(d) *5-Node Path*

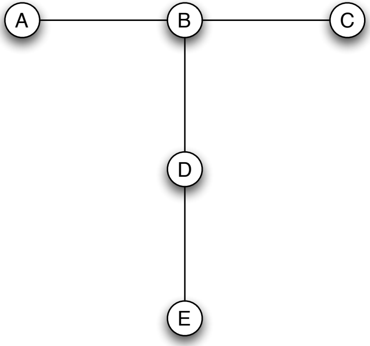
Does *C* have any power (i.e. fraction of money obtained) compared to other nodes?

Intuitively *B* and *D* have most of the power in the five node path network. The text states that in experiments, *C* has slightly more power than *A* or *E*.

Note that *C* is the most central node in terms of being on the most shortest paths. However, this has not translated into substantial bargaining power.

Another graph to consider

The previous examples may help us reason about the following example from the text.



The *network exchange* social experiment

The following network exchange social experiment (and variants) is repeated a number of *rounds* so that some form of learning is taking place. There are many variants and the text presents one particular setting:

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- For some known duration on time for a given round, negotiations take place for sharing say one $ on each edge. (We could allow larger and different sums for each edge). Once a pair have decided how to share the $, they leave the game
- There is one more important condition on the experiment; namely in any given round, the outcome has to be a matching. i.e., you're only allowed to deal with one other person
  - This is called the *1-exchange rule*

How much do these experimental findings depend on the exact setting.

We would, of course, like to have results that are robust and do not differ that much in the exact "details".

- Results are reasonably robust with regard to how much network information is available
- Results are consistent across different countries and different cultures

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  - In graph theory terms this is a b-matching; nodes can be adjacent to up to b edges in the matching
- Anonymity is important
  - How?

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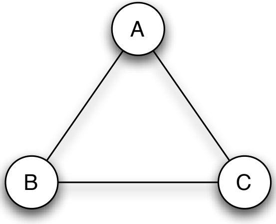
- Anonymity is important
  - How? Higher status individuals tend to inflate their "options", and those of lower status tend to underplay their options

Demo time!

I need two volunteers from the audience :)

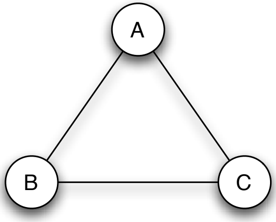


Question: For those who aren't volunteers – What solution will we converge to? As we go through the game, do you notice anything?

Do all experiments converge in a consistent manner?

In simple networks, each round tends to come to consistent outcomes within the specified time limits.

However, there are networks where this is not the case. Consider the following triangle graph:



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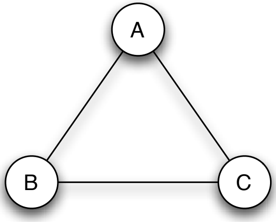

Question: Notice anything?

Any two of the nodes can wind up excluding the other. Hence we would expect that the final outcome in any round will be determined by the two nodes who get to settle just before the time deadline.

A mathematical perspective: The Nash Bargaining Solution

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John Nash (the same Nash who showed that all finite games have mixed equilibria) introduced a specific stable outcome, the *Nash Bargaining Solution*.

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An outcome in a network exchange process on a graph $G = (V, E)$ is a pair (M, v) where $M \subseteq E$ is a matching and the value function $v : V \rightarrow [0, 1]$ satisfies:

- For every edge $e = (x, y) \in M$, $v_x + v_y = 1$.
- If a node $x \in V$ is not part of the matching M (i.e. does not appear as a vertex in any edge $(x, y) \in M$), then $v_x = 0$.

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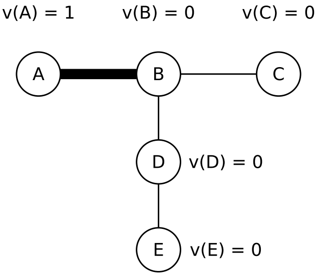

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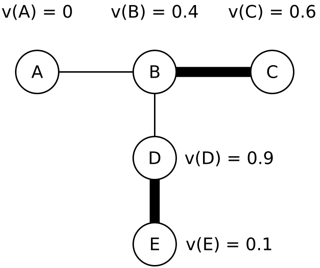

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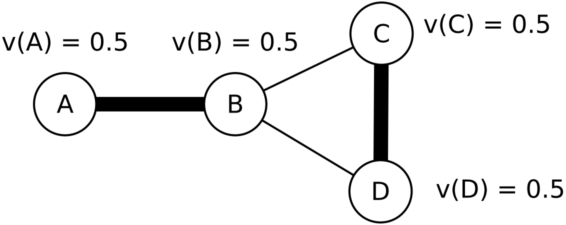
Suppose $v_{x'} + v_{y'} < 1$ for an edge $(x', y') \notin M$. Then the matching is unstable as there is a surplus of $s = 1 - v_{x'} - v_{y'}$ that can be shared between x' and y' and there is no reason for them not to share this surplus and increase both their values.

Which stable outcome?

Stable solutions are necessary but there can be many stable solutions and some are more natural (in the sense of corresponding to real behaviour) than others.



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- Suppose $(x, y) \in M$. What if x and y have other options other than to be in a given matching?
  - Suppose that x and y has the "outside options" of o_x and o_y respectively
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- Hence we get $v_x + v_y = 1$, with (x, y) in the matching.

Why extreme outcomes are not real outcomes

As stated earlier in this chapter, in the three node path example, the theory thus far would predict that B will obtain the entire \$. But we are told that in experiments, more typically B gets a fraction $\frac{5}{6}$ and one other node gets a fraction $\frac{1}{6}$.

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This can be explained once we understand that individuals (i.e., real people) are not driven solely by monetary payments. The "real value" to an individual may include some notion of fairness, pride, etc. When we consider these factors, we can see why in these experiments, extreme solutions (which sometimes are the only theoretically stable solutions) are not the actual outcome.

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In the following ultimatum game, we can perhaps better understand why participants tend to think beyond monetary rewards.

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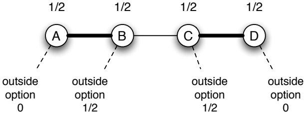
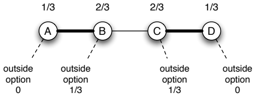
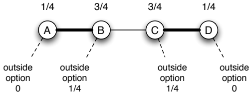
Aside: The Ultimatum Game is a little like the "I cut-you choose 2-person cake cutting algorithm" which ensures "fairness"

Not all stable outcomes are "natural"

As we stated, there can be many stable outcomes for a given network. But some do not appear as natural as others and, in particular, stable outcomes can be "extreme solutions" that do not represent what we believe to be more realistic. Which of the following stable outcomes might be more expected "in practice"?







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Can we give a mathematical explanation for why the $\frac{1}{3}, \frac{2}{3}$ split should be a likely outcome?

Balanced outcomes

It turns out that the $\frac{1}{3}, \frac{2}{3}$ split between A and B and also between C and D is what happens more in experiments and can be considered “more natural” in the following way.

The equal $\frac{1}{2}$ split amongst all parties does not reflect the relative much better bargaining position of B and C. In contrast, the $\frac{1}{4}, \frac{3}{4}$ split between A and B and also between C and D, seems to be giving B and C too much power given what we have been saying about how humans behave when taking say fairness, pride, etc into account.

Can we give a mathematical explanation for why the $\frac{1}{3}, \frac{2}{3}$ split should be a likely outcome?

It turns out that the $\frac{1}{3}, \frac{2}{3}$ split is the Nash Bargaining solution which we argued seemed like a fair way to divide up surpluses.

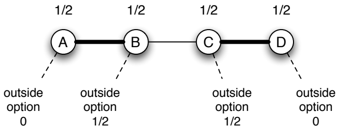
What is a balanced outcome?

Balanced outcomes

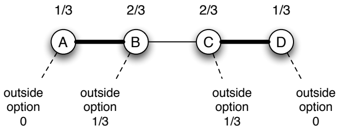
An outcome (M, v) is balanced if for every edge in the matching M, the split of money $\{v_x\}$ is the Nash bargaining solution for each node x, given the (best) outside options for each node.

Fact: For every exchange network with a stable outcome, there exists a balanced outcome.

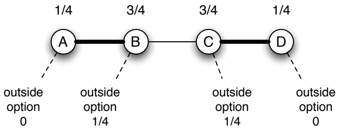
Balanced and unbalanced outcomes for the four node path



(a) *Not a balanced outcome*



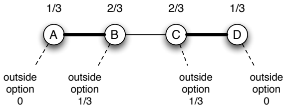
(b) *A balanced outcome*



(c) *Not a balanced outcome*

Checking that the balanced outcome is the Nash Bargaining solution

Let's check that the balanced outcome is indeed the Nash Bargaining solution.



Why is the best outside option for B (and similarly for C) equal to $\frac{1}{3}$?

Checking that the balanced outcome is the Nash Bargaining solution

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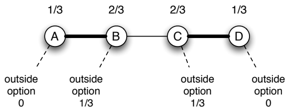

Why is the best outside option for B (and similarly for C) equal to $\frac{1}{3}$?

B has the option of offering $\frac{2}{3}$ (or maybe $\frac{2}{3} + \epsilon$ for some small $\epsilon > 0$) to entice C to leave its current match with D. Therefore, B can receive at most $\frac{1}{3} - \epsilon$. Of course, A has no outside option so we we can calculate that surplus for the matched edge (A, B) is $s = 1 - o_A - o_B = \frac{2}{3}$ and hence the Nash bargaining solution would be:

- $v_A = o_A + \frac{s}{2} = 0 + \frac{1}{3} = \frac{1}{3}$
- $v_B = o_B + \frac{s}{2} = \frac{1}{3} + \frac{1}{3} = \frac{2}{3}$

  which is consistent with the balanced outcome.

Similarly, C and D follow the Nash Bargaining solution.

Recap

- Bargaining in a Network Exchange Model
  - Power in the network exchange social experiment (Ch 12.1-12.3)
  - Stable outcomes (Ch 12.7)
  - The Ultimatum Game (Ch 12.6)
  - Balanced outcomes (Ch 12.5, 12.8)