# A Speed Read:
# WHERking to Meet the Need for Kidneys with NEAD Chains

*Project: Kidney Exchange*

TeamWHERk: Winnie Lau, Howard Yim, Eddie Shim, Rosalyn Lin
Professor Arash Asadpour
Decision Models
15 December 2015

# Overview

The Problem
Methodology
Model
Analysis & Conclusion

# The Problem

# Why focus on kidney disease?

1 out of every 3 Americans is at risk of CKD due to high blood pressure (hypertension), family history of CKD, or diabetes

**590,000,000+**

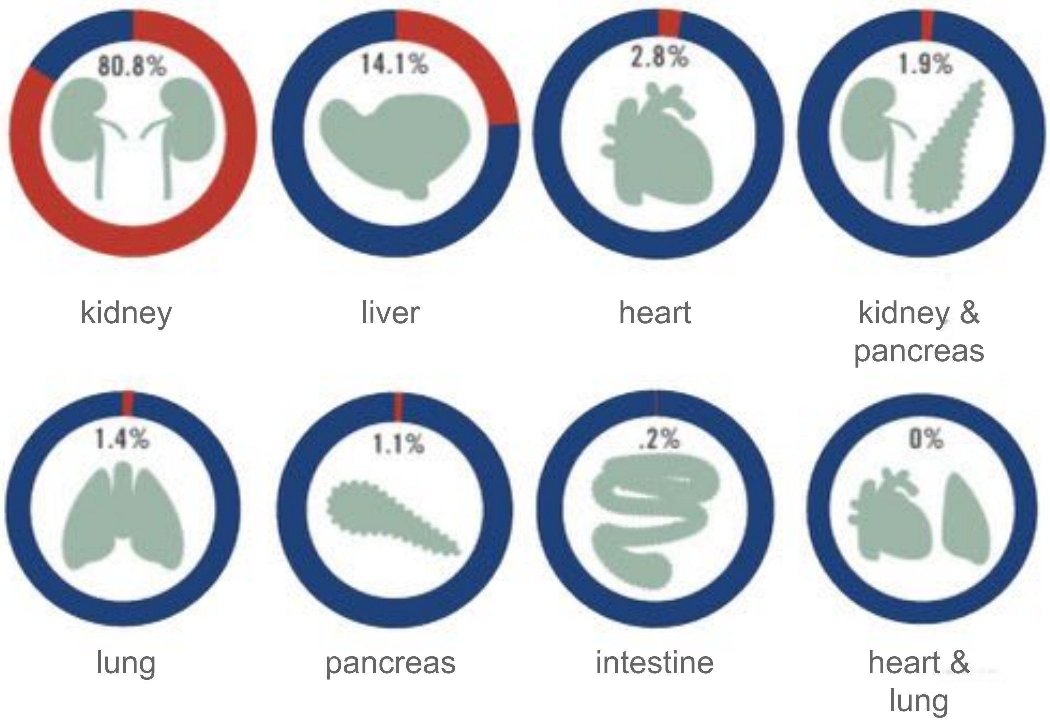
Americans have experienced kidney failure

people in need of a kidney transplant **95,000**

adults in the U.S. with chronic kidney disease (CKD) **20MM**

**9th** leading cause of death in the United States

# Kidneys are the organs in highest demand.



# What happens without a kidney donation?


# 1. Most patients' family & friends aren't matches.

There are 3 hurdles to receiving a kidney from a donor.

Healthy

Hurdle #1

Blood Compatible

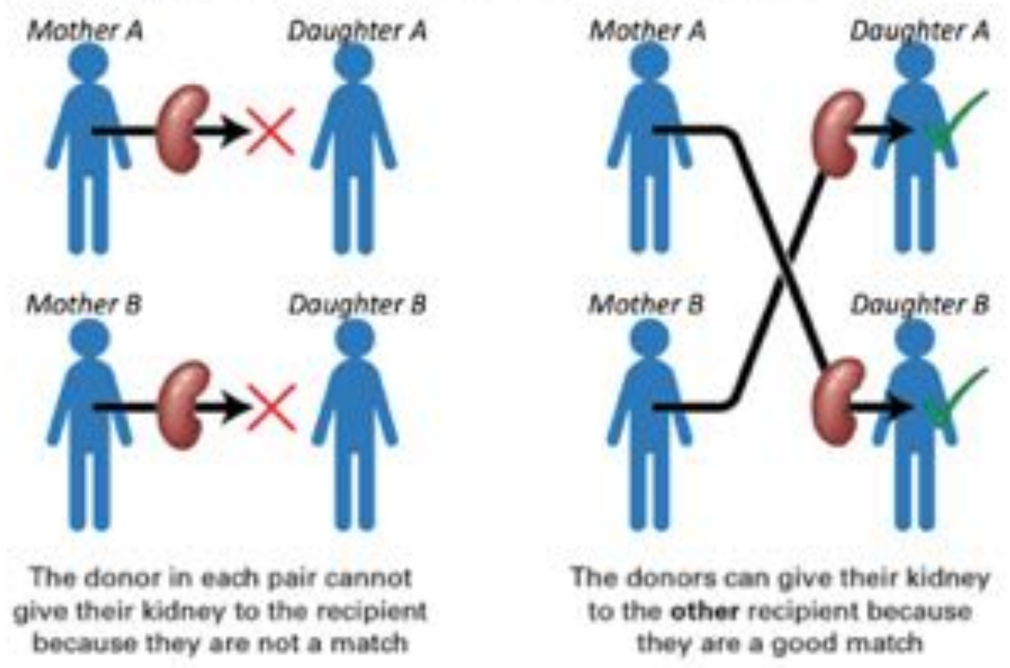
Hurdle #2

Tissue Compatible

Hurdle #3

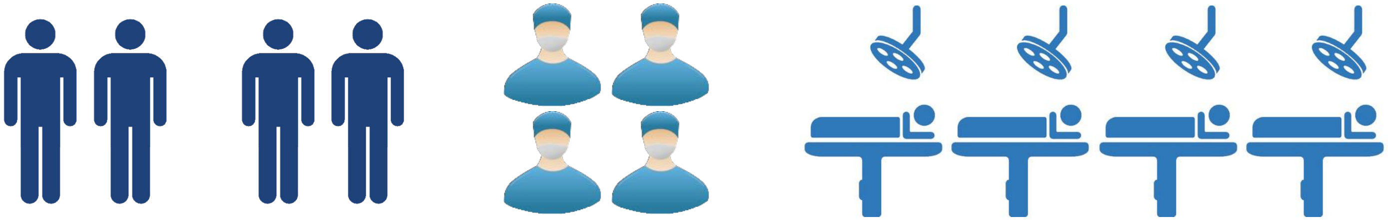
In families, brothers and sisters only have a 25% chance of matching.

# 2. Paired Exchanges are difficult to find.

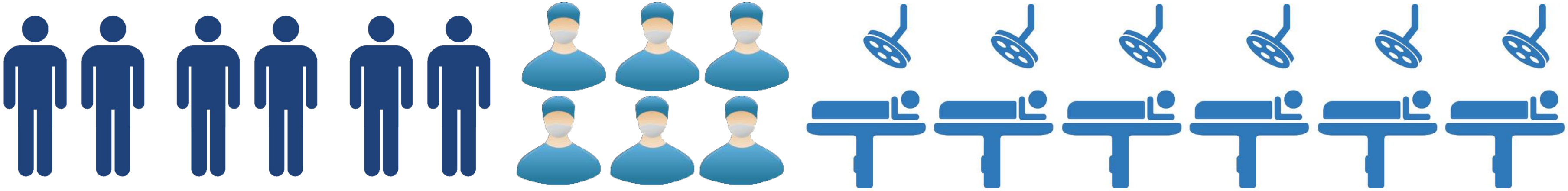


# 3. Law requires simultaneous surgeries for paired exchanges.

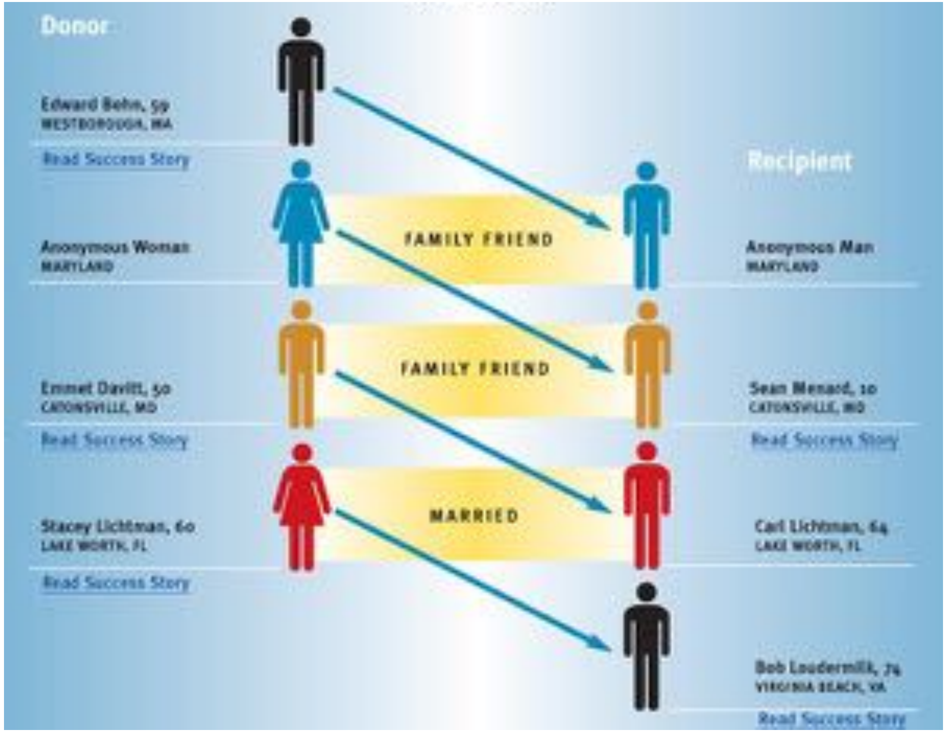
A cycle of 2 pairs requires 4 surgeons and 4 surgery rooms



A cycle of 3 pairs requires 6 surgeons and 6 surgery rooms



# The solution: Non-simultaneous Extended Altruistic Donor (NEAD) Chains




University of Maryland Medical Center
November 2009

# Methodology

# Simplification & Assumptions

- 1 living, altruistic non-directed donor (NDD) and 19 pairs
- The first donor is a living, altruistic non-directed (NDD) donor
- Only 2 tissue types: Rare (10% of population) and Frequent (90%)
- No constraint on chain length

# Step 1: Generation of 20 donors and 19 recipients

| Blood Type | Frequency |
|---|---|
| O | 48.14% |
| A | 33.73% |
| B | 14.28% |
| AB | 3.85% |

| Tissue Type | Frequency |
|---|---|
| Frequent | 90.00% |
| Rare | 10.00% |

ALLIANCE FOR PAIRED KIDNEY DONATION

Pair 3 ← Donor 3 - Recipient 3 ←

Pair 12 ← Donor 12 - Recipient 12 ←

*Assume D1-R1 to always be the living NDD

| Pairs | D-Blood | D-Tissue | R-Blood | R-Tissue |
|---|---|---|---|---|
| D1-R1 | O | Frequent | | |
| D2-R2 | B | Frequent | A | Frequent |
| D3-R3 | B | Rare | B | Frequent |
| D4-R4 | AB | Rare | B | Frequent |
| D5-R5 | A | Frequent | B | Rare |
| D6-R6 | AB | Rare | O | Frequent |
| D7-R7 | A | Frequent | AB | Frequent |
| D8-R8 | AB | Rare | O | Rare |
| D9-R9 | B | Frequent | O | Rare |
| D10-R10 | A | Frequent | A | Rare |
| D11-R11 | O | Frequent | O | Rare |
| D12-R12 | AB | Rare | B | Rare |
| D13-R13 | O | Frequent | O | Rare |
| D14-R14 | O | Frequent | B | Rare |
| D15-R15 | B | Frequent | AB | Rare |
| D16-R16 | A | Rare | A | Rare |
| D17-R17 | A | Frequent | O | Frequent |
| D18-R18 | A | Rare | O | Rare |
| D19-R19 | O | Frequent | O | Frequent |
| D20-R20 | B | Rare | O | Rare |

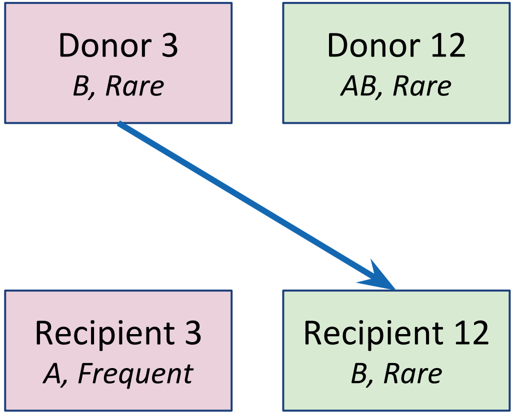
# Step 2: Extract possible pair matches

| Donor Blood Type | Possible Recipient Blood Types |
|---|---|
| O | O, A, B, AB |
| A | A, AB |
| B | B, AB |
| AB | AB |

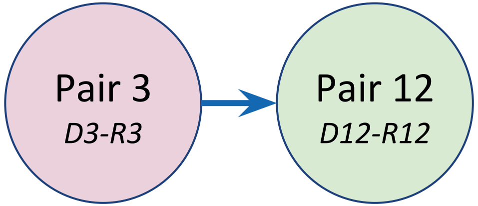
| Tissue Type | Possible Recipient Tissue Types |
|---|---|
| Frequent | Frequent |
| Rare | Rare, Frequent |

# Example

Given blood and tissue types,
Donor 3 can donate to Recipient 12




Pair 3 can donate to Pair 12




Network Nodes

# Step 3: Network optimization model

Decision Variables

$$Y_{i,j} \begin{cases} 1 \text{ if pair } i \text{ donates a kidney to pair } j \\ 0 \text{ if pair } i \text{ does not donate to pair } j \end{cases}$$

# Objective Function

$$\text{maximize} \sum_{i=1}^{no.\ of\ pairs} Y_{i,j} \text{ for all } j$$

Maximize the number of kidneys donated

## Constraints

$$\sum_{i=1}^{no.\ of\ pairs} Y_{NDD,j} - \sum_{i=1}^{no.\ of\ pairs} Y_{j,NDD} = 1$$

Non-directed donor (D1-R1) must donate first

$$\sum_{i=1}^{no.\ of\ pairs} Y_{i,j} - \sum_{i=1}^{no.\ of\ pairs} Y_{j,i} = 0$$

Inter-nodes conservation of flow

$$\sum_{i=1}^{no.\ of\ pairs} Y_{end\ pair,j} - \sum_{i=1}^{no.\ of\ pairs} Y_{j,end\ pair} = -1$$

End of chain — last pair does not donate

$$\sum_{i=1}^{no.\ of\ pairs} Y_{i} + \sum_{i=1}^{no.\ of\ pairs} i \leq 1 + \sum_{i=1}^{no.\ of\ pairs} i$$

Each pair can only donate one kidney

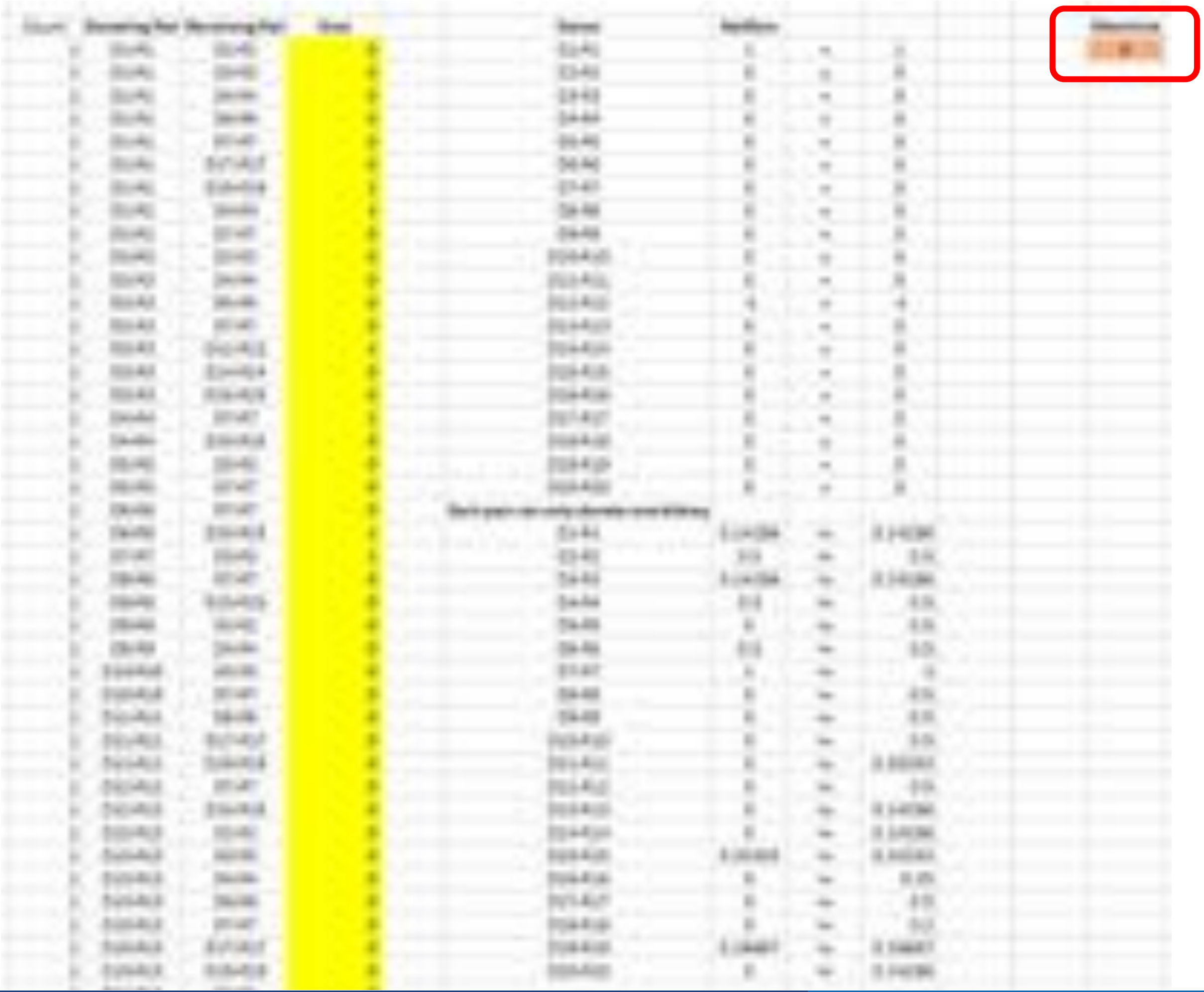
# Implemented Model

ALLIANCE FOR PAIRED KIDNEY DONATION

# Step 1: Generation of 1 NDD and 19 pairs on Crystal Ball

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bucket | Blood Type | Frequency | | Bucket | Tissue Type | Frequency | | |
| 2 | 1 | O | 0.4814 | | 1 | Rare | 0.1 | | |
| 3 | 2 | A | 0.3373 | | 2 | Frequent | 0.9 | | |
| 4 | 3 | B | 0.2834 | | | | | | |
| 5 | 4 | AB | 0.0385 | | | | | | |
| 6 | | | | | | | | | |
| 7 | DonorB | D-Blood | DonorT | D-Tissue | | RecipientB | R-Blood | RecipientT | R-Tissue |
| 8 | 4 | AB | 1 | Rare | | 3 | B | 2 | Frequent |
| 9 | 1 | O | 2 | Frequent | | 3 | B | 2 | Frequent |
| 10 | 4 | AB | 1 | Rare | | 4 | AB | 1 | Rare |
| 11 | 1 | O | 1 | Rare | | 4 | AB | 1 | Rare |
| 12 | 2 | A | 1 | Rare | | 4 | AB | 2 | Frequent |
| 13 | 4 | AB | 2 | Frequent | | 1 | O | 1 | Rare |
| 14 | 1 | O | 1 | Rare | | 2 | A | 2 | Frequent |
| 15 | 3 | B | 2 | Frequent | | 2 | A | 2 | Frequent |
| 16 | 3 | B | 1 | Rare | | 1 | O | 2 | Frequent |
| 17 | 1 | O | 1 | Rare | | 2 | A | 2 | Frequent |
| 18 | 4 | AB | 1 | Rare | | 1 | O | 2 | Frequent |
| 19 | 4 | AB | 2 | Frequent | | 1 | O | 1 | Rare |
| 20 | 3 | B | 1 | Rare | | 1 | O | 2 | Frequent |

- **DonorB**: Donor blood type given by CB.Custom
- **DonorT**: Donor tissue type given by CB.Custom
- **RecipientB**: Donor blood type given by CB.Custom
- **RecipientT**: Donor tissue type given by CB.Custom
- V-lookup to return associating text



Chain of 8 transplants in a sample of 19 pairs with 82 possible matches

# Extending the Model: Stochastic Data

# Stochastic Model: Data Generation

| | Blood | Tissue |
|---|---|---|
| NDD | O | Frequent |

| Pairs | D-Bloo | D-Tissu | R-Bloo | R-Tissue |
|---|---|---|---|---|
| D1-R1 | A | Frequen | AB | Frequent |
| D2-R2 | AB | Rare | AB | Frequent |
| D3-R3 | AB | Frequen | O | Rare |
| D4-R4 | AB | Frequen | AB | Frequent |
| D5-R5 | B | Frequen | O | Rare |
| D6-R6 | O | Frequen | O | Frequent |
| D7-R7 | O | Rare | AB | Frequent |
| D8-R8 | AB | Frequen | O | Rare |
| D9-R9 | O | Rare | AB | Frequent |
| D10-R10 | A | Rare | AB | Rare |
| D11-R11 | O | Rare | A | Frequent |
| D12-R12 | AB | Frequen | A | Frequent |
| D13-R13 | B | Frequen | AB | Frequent |
| D14-R14 | AB | Frequen | B | Rare |
| D15-R15 | A | Frequen | A | Rare |
| D16-R16 | O | Frequen | B | Frequent |
| D17-R17 | A | Frequen | B | Frequent |
| D18-R18 | A | Rare | O | Rare |
| D19-R19 | A | Frequen | A | Rare |
| D20-R20 | O | Frequen | A | Rare |

| Donor Pair Name | Receiver Pair Name | D-Blood | D-Tissue | R-Blood | R-Tissue | Blood Feasible | Tissue Feasibility | Pair Feasibility | Total Feasible Pairs | Feasible Pairs % |
|---|---|---|---|---|---|---|---|---|---|---|
| D1-R1 | D2-R2 | A | Frequent | AB | Frequent | 1 | 1 | 1 | 112 | 0.505263158 |
| D1-R1 | D3-R3 | A | Frequent | O | Rare | 0 | 0 | 0 | | |
| D1-R1 | D4-R4 | A | Frequent | AB | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D5-R5 | A | Frequent | O | Rare | 0 | 0 | 0 | | |
| D1-R1 | D6-R6 | A | Frequent | O | Frequent | 0 | 1 | 0 | | |
| D1-R1 | D7-R7 | A | Frequent | AB | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D8-R8 | A | Frequent | O | Rare | 0 | 0 | 0 | | |
| D1-R1 | D9-R9 | A | Frequent | AB | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D10-R10 | A | Frequent | AB | Rare | 1 | 0 | 0 | | |
| D1-R1 | D11-R11 | A | Frequent | A | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D12-R12 | A | Frequent | A | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D13-R13 | A | Frequent | AB | Frequent | 1 | 1 | 1 | | |
| D1-R1 | D14-R14 | A | Frequent | B | Rare | 0 | 0 | 0 | | |
| D1-R1 | D15-R15 | A | Frequent | A | Rare | 1 | 0 | 0 | | |
| D1-R1 | D16-R16 | A | Frequent | B | Frequent | 0 | 1 | 0 | | |
| D1-R1 | D17-R17 | A | Frequent | B | Frequent | 0 | 1 | 0 | | |
| D1-R1 | D18-R18 | A | Frequent | O | Rare | 0 | 0 | 0 | | |
| D1-R1 | D19-R19 | A | Frequent | A | Rare | 1 | 0 | 0 | | |
| D1-R1 | D20-R20 | A | Frequent | A | Rare | 1 | 0 | 0 | | |
| D2-R2 | D1-R1 | AB | Rare | AB | Frequent | 1 | 1 | 1 | | |
| D2-R2 | D3-R3 | AB | Rare | O | Rare | 0 | 1 | 0 | | |
| D2-R2 | D4-R4 | AB | Rare | AB | Frequent | 1 | 1 | 1 | | |
| D2-R2 | D5-R5 | AB | Rare | O | Rare | 0 | 1 | 0 | | |
| D2-R2 | D6-R6 | AB | Rare | O | Frequent | 0 | 1 | 0 | | |
| D2-R2 | D7-R7 | AB | Rare | AB | Frequent | 1 | 1 | 1 | | |
| D2-R2 | D8-R8 | AB | Rare | O | Rare | 0 | 1 | 0 | | |
| D2-R2 | D9-R9 | AB | Rare | AB | Frequent | 1 | 1 | 1 | | |
| D2-R2 | D10-R10 | AB | Rare | AB | Rare | 1 | 1 | 1 | | |
| D2-R2 | D11-R11 | AB | Rare | A | Frequent | 0 | 1 | 0 | | |
| D2-R2 | D12-R12 | AB | Rare | A | Frequent | 0 | 1 | 0 | | |
| D2-R2 | D13-R13 | AB | Rare | AB | Frequent | 1 | 1 | 1 | | |
| D2-R2 | D14-R14 | AB | Rare | B | Rare | 0 | 1 | 0 | | |
| D2-R2 | D15-R15 | AB | Rare | A | Rare | 0 | 1 | 0 | | |

# Custom Probability Distributions

| Donor Blood Type | Possible Recipient Blood Types |
| --- | --- |
| O | 48.14% |
| A | 33.73% |
| B | 14.28% |
| AB | 3.85% |

| Tissue Type | Possible Recipient Tissue Types |
| --- | --- |
| Frequent | 90% |
| Rare | 10% |

# Finding Feasible Pairs: Macro

```
Function checkFeasibility(Donor As String, Recipient As String)
    Select Case Donor
        Case "A"
            If Recipient = "A" Or Recipient = "AB" Then checkFeasibility = 1
        Case "B"
            If Recipient = "B" Or Recipient = "AB" Then checkFeasibility = 1
        Case "AB"
            If Recipient = "AB" Then checkFeasibility = 1
        Case "O"
            If Recipient = "A" Or Recipient = "B" Or Recipient = "AB" Or Recipient = "O" Then
checkFeasibility = 1
        Case "Frequent"
            If Recipient = "Frequent" Then checkFeasibility = 1
        Case "Rare"
            If Recipient = "Rare" Or Recipient = "Frequent" Then checkFeasibility = 1
    End Select
End Function
```

# Overall Flow of Model

Stochastic Model → Feasible Pairs → Network Optimization Model

# Combined Model w/ Stochastic Data

| Count | Donating Pair | Receiving Pair | Pair Feasibility | Give |
|---|---|---|---|---|
| 1 | D1-R1 | D2-R2 | 1 | |
| 1 | D1-R1 | D3-R3 | 1 | |
| 1 | D1-R1 | D4-R4 | 0 | |
| 1 | D1-R1 | D5-R5 | 0 | |
| 1 | D1-R1 | D6-R6 | 0 | |
| 1 | D1-R1 | D7-R7 | 0 | |
| 1 | D1-R1 | D8-R8 | 0 | |
| 1 | D1-R1 | D9-R9 | 1 | |
| 1 | D1-R1 | D10-R10 | 0 | |
| 1 | D1-R1 | D11-R11 | 1 | |
| 1 | D1-R1 | D12-R12 | 0 | |
| 1 | D1-R1 | D13-R13 | 0 | |
| 1 | D1-R1 | D14-R14 | 0 | |
| 1 | D1-R1 | D15-R15 | 1 | |
| 1 | D1-R1 | D16-R16 | 0 | |
| 1 | D1-R1 | D17-R17 | 1 | |
| 1 | D1-R1 | D18-R18 | 0 | |
| 1 | D1-R1 | D19-R19 | 0 | |
| 1 | D1-R1 | D20-R20 | 0 | |
| 1 | D2-R2 | D1-R1 | 0 | |
| 1 | D2-R2 | D3-R3 | 1 | |
| 1 | D2-R2 | D4-R4 | 1 | |
| 1 | D2-R2 | D5-R5 | 0 | |
| 1 | D2-R2 | D6-R6 | 0 | |
| 1 | D2-R2 | D7-R7 | 1 | |
| 1 | D2-R2 | D8-R8 | 1 | |
| 1 | D2-R2 | D9-R9 | 1 | |

| Donor | Net Flow | | |
|---|---|---|---|
| D1-R1 | 0 | = | 1 |
| D2-R2 | 0 | = | 0 |
| D3-R3 | 0 | = | 0 |
| D4-R4 | 0 | = | 0 |
| D5-R5 | 0 | = | 0 |
| D6-R6 | 0 | = | 0 |
| D7-R7 | 0 | = | 0 |
| D8-R8 | 0 | = | 0 |
| D9-R9 | 0 | = | 0 |
| D10-R10 | 0 | = | 0 |
| D11-R11 | 0 | = | 0 |
| D12-R12 | 0 | = | 0 |
| D13-R13 | 0 | = | 0 |
| D14-R14 | 0 | = | 0 |
| D15-R15 | 0 | = | 0 |
| D16-R16 | 0 | = | 0 |
| D17-R17 | 0 | = | 0 |
| D18-R18 | 0 | = | 0 |
| D19-R19 | 0 | = | 0 |
| D20-R20 | 0 | = | -1 |

Each pair can only donate one kidney

| | | | |
|---|---|---|---|
| D1-R1 | 0 | <= | 0.052631579 |
| D2-R2 | 0 | <= | 0.052631579 |
| D3-R3 | 0 | <= | 0.052631579 |
| D4-R4 | 0 | <= | 0.052631579 |
| D5-R5 | 0 | <= | 0.052631579 |

| | | |
|---|---|---|
| Pair Feasibility | = | 1 |

Maximize

# Additional Constraint to Incorporate Stochastic Data

$$Pair\ Feasibility_{ij} >= Give_{ij}$$

# Potential Results from Incorporating Stochastic

- Effects of altruistic donor's blood & tissue type on the optimal chain generated (i.e. Given a large enough pool of patients, does it matter if the first donor is O & R versus AB & F?)
- Optimal chain length (convergence rate of simulated chain lengths)

# Analysis & Conclusion

ALLIANCE FOR PAIRED KIDNEY DONATION

# Our Model's Solution

Length of chain = 8

Success rate of 8/19 = 42%

restricting donor pair

D1-R1 to D19-R19

D19-R19 to D6 R6

D6-R6 to D15-R15

D15-R15 to D2-R2

D2-R2 to D4-R4

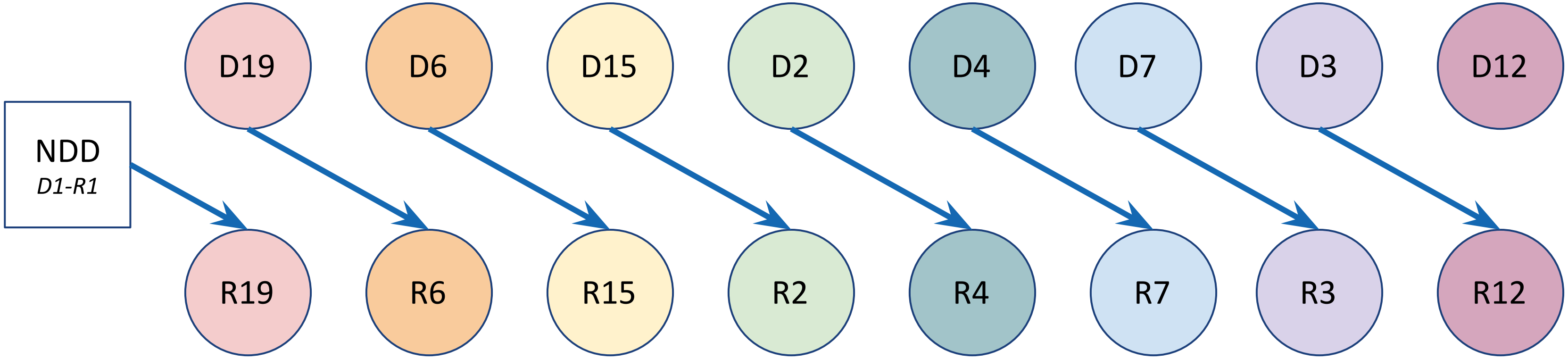
D4-R4 to D7-R7

D7-R7 to D3-R3

D3-R3 to D12-R12

sole receiver

# 8 Lives Saved!



# Limitations

- ❖ Integrating stochastic data with network optimization model
- ❖ Lack of actual patient data

# Refining the Model

- Incorporating weights for each edge that takes into account
  - PRA percentages instead of “Rare” and “Frequent” tissue types
  - Degree of compatibility
  - Age
  - Wait time
  - Level of urgency
  - Geographic proximity

- Optimizing for both kidney and plasma transplants

# Thank you!

# Questions?