Tasks?

- Mechanics
  - Record keeping
  - Administration
  - Scheduling
  - …
- Diagnosis
- Prognosis
- Therapy
Types of Decision Support

• “Doctor's Assistant” for clinicians at any level of training
• Expert (specialist) consultation for non-specialists
• Monitoring and error detection
• Critiquing, what-if
• Guiding patient-controlled care
• Education and Training
• Contribution to medical research
• …
Two Historical Views on How to Build Expert Systems

- Great cleverness
  - Powerful inference abilities

- Great stores of knowledge
  - Possibly limited ability to infer, but
  - Vast storehouse of relevant knowledge, indexed in an easy-to-apply form
Change over 30 years

• 1970’s: human knowledge, not much data
• 2000’s: vast amounts of data, traditional human knowledge (somewhat) in doubt
• Could we “re-discover” all of medicine from data? *I think not!*
• Should we focus on methods for reasoning with uncertain data? *Absolutely!*
Simplest Example

- Relationship between a diagnostic conclusion and a diagnostic test

<table>
<thead>
<tr>
<th></th>
<th>Disease Present</th>
<th>Disease Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Positive</strong></td>
<td>True Positive</td>
<td>False Positive</td>
</tr>
<tr>
<td></td>
<td>TP+FP</td>
<td></td>
</tr>
<tr>
<td><strong>Test Negative</strong></td>
<td>False Negative</td>
<td>True Negative</td>
</tr>
<tr>
<td></td>
<td>FN+TN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TP+FN</td>
<td>FP+TN</td>
</tr>
</tbody>
</table>
## Definitions

<table>
<thead>
<tr>
<th></th>
<th>Disease Present</th>
<th>Disease Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Positive</td>
<td>True Positive</td>
<td>False Positive</td>
</tr>
<tr>
<td></td>
<td>TP+FP</td>
<td></td>
</tr>
<tr>
<td>Test Negative</td>
<td>False Negative</td>
<td>True Negative</td>
</tr>
<tr>
<td></td>
<td>FN+TN</td>
<td></td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TP+FN</td>
<td>FP+TN</td>
<td></td>
</tr>
</tbody>
</table>

**Sensitivity (true positive rate):** \( \frac{TP}{TP+FN} \)

**False negative rate:** \( 1 - \text{Sensitivity} = \frac{FN}{TP+FN} \)

**Specificity (true negative rate):** \( \frac{TN}{FP+TN} \)

**False positive rate:** \( 1 - \text{Specificity} = \frac{FP}{FP+TN} \)

**Positive Predictive Value:** \( \frac{TP}{TP+FP} \)

**Negative Predictive Value:** \( \frac{TN}{FN+TN} \)
Cancer Test

• We discover a cheap, 95% accurate test for cancer.
• Give it to “Mrs. Jones”, the next person who walks by 77 Mass Ave.
• Result is positive.
• What is the probability that Mrs. Jones has cancer?
Figuring out Cancer Probability

Assume Ca in 1% of general population:

\[
\frac{950}{950 + 4950} = .161
\]
At the Extremes

• If Ca probability in population is 0.1%,
  – Then post positive result, \( p(Ca) = 1.87\% \)

• If Ca probability in population is 50%,
  – Then post-positive result, \( p(Ca) = 95\% \)
Bayes’ Rule

\[ P(D|T) = \frac{P(D)P(T|D)}{P(D)P(T|D) + P(\bar{D})P(T|\bar{D})} \]
Odds/Likelihood Form

\[
P(D \mid T) = \frac{P(D)P(T \mid D)}{P(D)P(T \mid D) + P(\overline{D})P(T \mid \overline{D})}
\]

\[
P(\overline{D} \mid T) = \frac{P(\overline{D})P(T \mid \overline{D})}{P(D)P(T \mid D) + P(\overline{D})P(T \mid \overline{D})}
\]

\[
\frac{P(D \mid T)}{P(\overline{D} \mid T)} = \frac{P(D)}{P(\overline{D})} \frac{P(T \mid D)}{P(T \mid \overline{D})}
\]

\[
O(D \mid T) = O(D) L(T \mid D)
\]

\[
W(D \mid T) = W(D) + W(T \mid D)
\]
Test Thresholds

- FN
- FP

T
Wonderful Test
Test Thresholds Change Trade-off between Sensitivity and Specificity
Receiver Operator Characteristic (ROC) Curve

TPR (sensitivity)

FPR (1-specificity)
What makes a better test?

FPR (1-specificity) vs. TPR (sensitivity)

- Superb
- OK
- Worthless
DeDombal, et al. Experience 1970’s & 80’s

• “Idiot Bayes” for appendicitis
• 1. Based on expert estimates -- lousy
• 2. Statistics -- better than docs
• 3. Different hospital -- lousy again
• 4. Retrained on local statistics -- good
Rationality

- Behavior is a continued sequence of choices, interspersed by the world’s responses
- Best action is to make the choice with the greatest expected value
- … decision analysis
Example: Gangrene

• From Pauker’s “Decision Analysis Service” at New England Medical Center Hospital, late 1970’s.

• Man with gangrene of foot

• Choose to amputate foot or treat medically

• If medical treatment fails, patient may die or may have to amputate whole leg.

• What to do? How to reason about it?
Decision Tree for Gangrene

1. Amputate foot
   - Live: 0.99, Cost: 850
   - Die: 0.01

2. Medicine
   - Full recovery: 0.7, Cost: 1000
   - Worse: 0.25
     - Live: 0.6, Cost: 995
     - Die: 0.4
   - Die: 0.05
Evaluating the Decision Tree

- Amputate foot
  - Live (.99)
    - Die (.01)
  - Medicine
    - Full recovery (.7)
      - Live (.98)
        - Die (.02)
      - Worse (.25)
        - Die (.05)
    - Die (.05)
    - Medicine
      - Live (.6)
        - Die (.4)
Decision Analysis:
Evaluating Decision Trees

- Outcome: directly estimate value
- Decision: value is that of the choice with the greatest expected value
- Chance: expected value is sum of (probabilities x values of results)
- “Fold back” from outcomes to current decision.
- Sensitivity analyses often more important than result(!)
HELP System uses D.A.

Fig. 29. Effect of age of patient and $M_c$ (mortality for appendicitis without operation) on the probability threshold (point of crossing zero $\Delta u$ line) for decision to operate.

Utility Analysis of Appendectomy

Fig. 30. Effect of patient's salary and assumed value of one day of good health ($70 or $140) on decision to operate for appendicitis.
Threshold

• Benefit $B = U(\text{treat dis}) - U(\text{no treat dis})$
• Cost $C = U(\text{no treat no dis}) - U(\text{treat no dis})$
• Threshold probability for treatment:

$$T = \frac{1}{\frac{B}{C} + 1}$$

Pauker, Kassirer, NEJM 1975
Test/Treat Threshold

Pauker, Kassirer, NEJM 1980
More Complex Decision Analysis Issues

- Repeated decisions
- Accumulating disutilities
- Dependence on history
- Cohorts & state transition models
- Explicit models of time
- Uncertainty in the uncertainties
- Determining utilities
  - Lotteries, ...
- Qualitative models
Example: Acute Renal Failure

• Choice of a handful (8) of therapies (antibiotics, steroids, surgery, etc.)
• Choice of a handful (3) of invasive tests (biopsies, IVP, etc.)
• Choice of 27 diagnostic “questions” (patient characteristics, history, lab values, etc.)
• Underlying cause is one of 14 diseases
  – We assume one and only one disease
Decision Tree for ARF

• Choose:
  – Surgery for obstruction
  – Treat with antibiotics
  – Perform pyelogram
  – Perform arteriography
  – Measure patient’s temperature
  – Determine if there is proteinuria
  – …
Decision Tree for ARF

- Surgery for obstruction
- Treat with antibiotics
- Perform pyelogram
- Perform arteriography
- Measure patient’s temperature
- Determine if there is proteinuria

Value = ???
What happens when we act?

• Treatment: leads to few possible outcomes
  – different outcomes have different probabilities
    • probabilities depend on distribution of disease probabilities
  – value of outcome can be directly determined
    • value may depend on how we got there (see below)
    • therefore, value of a treatment can be determined by expectation

• Test: lead to few results, revise probability distribution of diseases, and impose disutility

• Questions: lead to few results, revise probability distribution
Full decision tree
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Condition</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATN</td>
<td>Acute tubular necrosis</td>
<td>0.250</td>
</tr>
<tr>
<td>FARF</td>
<td>Functional acute renal failure</td>
<td>0.400</td>
</tr>
<tr>
<td>OBSTR</td>
<td>Urinary tract obstruction</td>
<td>0.100</td>
</tr>
<tr>
<td>AGN</td>
<td>Acute glomerulonephritis</td>
<td>0.100</td>
</tr>
<tr>
<td>CN</td>
<td>Renal cortical necrosis</td>
<td>0.020</td>
</tr>
<tr>
<td>HS</td>
<td>Hepatorenal syndrome</td>
<td>0.005</td>
</tr>
<tr>
<td>PYE</td>
<td>Pyelonephritis</td>
<td>0.010</td>
</tr>
<tr>
<td>AE</td>
<td>Atheromatous Emboli</td>
<td>0.003</td>
</tr>
<tr>
<td>RI</td>
<td>Renal infarction (bilateral)</td>
<td>0.002</td>
</tr>
<tr>
<td>RVT</td>
<td>Renal vein thrombosis</td>
<td>0.002</td>
</tr>
<tr>
<td>VASC</td>
<td>Renal vasculitis</td>
<td>0.050</td>
</tr>
<tr>
<td>SCL</td>
<td>Scleroderma</td>
<td>0.002</td>
</tr>
<tr>
<td>CGAE</td>
<td>Chronic glomerulonephritis, acute exacerbation</td>
<td>0.030</td>
</tr>
<tr>
<td>MH</td>
<td>Malignant hypertension &amp; nephrosclerosis</td>
<td>0.030</td>
</tr>
</tbody>
</table>
ARF’s Database: P(obs|D)

<table>
<thead>
<tr>
<th>Proteinuria Diseases</th>
<th>Probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>ATN</td>
<td>0.1</td>
</tr>
<tr>
<td>FARF</td>
<td>0.8</td>
</tr>
<tr>
<td>OBSTR</td>
<td>0.7</td>
</tr>
<tr>
<td>AGN</td>
<td>0.01</td>
</tr>
<tr>
<td>CN</td>
<td>0.01</td>
</tr>
<tr>
<td>HS</td>
<td>0.8</td>
</tr>
<tr>
<td>PYE</td>
<td>0.4</td>
</tr>
<tr>
<td>AE</td>
<td>0.1</td>
</tr>
<tr>
<td>RI</td>
<td>0.1</td>
</tr>
<tr>
<td>RVT</td>
<td>0.001</td>
</tr>
<tr>
<td>VASC</td>
<td>0.01</td>
</tr>
<tr>
<td>SCL</td>
<td>0.1</td>
</tr>
<tr>
<td>CGAE</td>
<td>0.001</td>
</tr>
<tr>
<td>MH</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Questions

- Blood pressure at onset
- proteinuria
- casts in urine sediment
- hematuria
- history of prolonged hypotension
- urine specific gravity
- large fluid loss preceding onset
- kidney size
- urine sodium
- strep infection within three weeks
- urine volume
- recent surgery or trauma
- age
- papilledema
- flank pain
- skin, intestinal or lung lesions

- history of proteinuria
- symptoms of bladder obstruction
- exposure to nephrotoxic drugs
- disturbance in clotting mechanism
- pyuria
- bacteriuria
- sex
- transfusion within one day
- jaundice or ascites
- ischemia of extremities or aortic aneurism
- atrial fibrillation or recent MI
Invasive tests and treatments

• Tests
  – biopsy
  – retrograde pyelography
  – transfemoral arteriography

• Treatments
  – steroids
  – conservative therapy
  – iv-fluids
  – surgery for urinary tract obstruction
  – antibiotics
  – surgery for clot in renal vessels
  – antihypertensive drugs
  – heparin
Updating probability distribution

\[ P_{i+1}(D_j) = \frac{P_i(D_j)P(S|D_j)}{\sum_{k=1}^{n} P_i(D_k)P(S|D_k)} \]

Bayes’ rule
Value of treatment

- Three results: improved, unchanged, worsened
  - each has an innate value, modified by “tolls” paid on the way

- Probabilities depend on underlying disease probability distribution

```
   Tx
    /   \
   /     \
 pU    pI
    /     \
 U     I
    /     \
  V(U)   V(I)
```

```
   W
    \   
     \  
      \ W
```

V(U) V(W)
## Modeling treatment

<table>
<thead>
<tr>
<th>Steroids</th>
<th>improved</th>
<th>unchanged</th>
<th>worse</th>
</tr>
</thead>
<tbody>
<tr>
<td>atn</td>
<td>0.60</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>farf</td>
<td>0.05</td>
<td>0.35</td>
<td>0.60</td>
</tr>
<tr>
<td>obstr</td>
<td>0.05</td>
<td>0.60</td>
<td>0.35</td>
</tr>
<tr>
<td>agn</td>
<td>0.40</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>cn</td>
<td>0.05</td>
<td>0.75</td>
<td>0.20</td>
</tr>
<tr>
<td>hs</td>
<td>0.05</td>
<td>0.05</td>
<td>0.90</td>
</tr>
<tr>
<td>pye</td>
<td>0.05</td>
<td>0.05</td>
<td>0.90</td>
</tr>
<tr>
<td>ae</td>
<td>0.05</td>
<td>0.70</td>
<td>0.25</td>
</tr>
<tr>
<td>ri</td>
<td>0.01</td>
<td>0.14</td>
<td>0.85</td>
</tr>
<tr>
<td>rvt</td>
<td>0.10</td>
<td>0.30</td>
<td>0.60</td>
</tr>
<tr>
<td>vasc</td>
<td>0.15</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>scl</td>
<td>0.05</td>
<td>0.05</td>
<td>0.90</td>
</tr>
<tr>
<td>cgae</td>
<td>0.40</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>mh</td>
<td>0.05</td>
<td>0.05</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Utilities:**

- improved: 5000
- unchanged: -2500
- worse: -5000
Modeling test: transfemoral arteriography

<table>
<thead>
<tr>
<th></th>
<th>p(clot)</th>
<th>cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>atn</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>farf</td>
<td>0.01</td>
<td>800</td>
</tr>
<tr>
<td>obstr</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>agn</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>cn</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>hs</td>
<td>0.01</td>
<td>800</td>
</tr>
<tr>
<td>pye</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>ae</td>
<td>0.03</td>
<td>800</td>
</tr>
<tr>
<td>ri</td>
<td>0.85</td>
<td>500</td>
</tr>
<tr>
<td>rvt</td>
<td>0.50</td>
<td>500</td>
</tr>
<tr>
<td>vasc</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>scl</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>cgae</td>
<td>0.01</td>
<td>500</td>
</tr>
<tr>
<td>mh</td>
<td>0.01</td>
<td>500</td>
</tr>
</tbody>
</table>
How large is the tree?

- Infinite, or at least \((27+3+8)^{(27+3+8)}, \sim 10^{60}\)
- What can we do?
  - Assume any action is done only once
  - Order:
    - questions
    - tests
    - treatments
- \(27! \times 4 \times 3 \times 2 \times 8, \sim 10^{30}\)
- Search, with a *myopic evaluation function*
  - like game-tree search; what’s the static evaluator?
  - Measure of certainty in the probability distribution
How many questions needed?

• How many items can you distinguish by asking 20 (binary) questions? $2^{20}$
• How many questions do you need to ask to distinguish among $n$ items? $\log_2(n)$
• Entropy of a probability distribution is a measure of how certainly the distribution identifies a single answer; or how many more questions are needed to identify it
Entropy of a distribution

\[ H_i(P_1, \ldots, P_n) = \sum_{j=1}^{n} - P_j \log_2 P_j \]

For example:
- \( H(.5, .5) = 1.0 \)
- \( H(.1, .9) = 0.47 \)
- \( H(.01, .99) = 0.08 \)
- \( H(.001, .999) = 0.01 \)

- \( H(.33, .33, .33) = 1.58 (!) \)
- \( H(.005, .455, .5) = 1.04 \)
- \( H(.005, .995, 0) = 0.045 \)

(!) -- should use \( \log_n \)
Interacting with ARF in 1973

Question 1: What is the patient's age?
1 0-10
2 11-30
3 31-50
4 51-70
5 Over 70
Reply: 5

The current distribution is:

<table>
<thead>
<tr>
<th>Disease</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>FARF</td>
<td>0.58</td>
</tr>
<tr>
<td>IBSTR</td>
<td>0.22</td>
</tr>
<tr>
<td>ATN</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Question 2: What is the patient's sex?
1 Male
2 Pregnant Female
3 Non-pregnant Female
Reply: 1

...
ARF in 1994

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ATN</td>
<td>0.000</td>
</tr>
<tr>
<td>FARF</td>
<td>0.006</td>
</tr>
<tr>
<td>OBSTR</td>
<td>0.966</td>
</tr>
<tr>
<td>AGN</td>
<td>0.000</td>
</tr>
<tr>
<td>CN</td>
<td>0.000</td>
</tr>
<tr>
<td>HS</td>
<td>0.000</td>
</tr>
<tr>
<td>PVE</td>
<td>0.027</td>
</tr>
<tr>
<td>AE</td>
<td>0.000</td>
</tr>
<tr>
<td>RI</td>
<td>0.000</td>
</tr>
<tr>
<td>RVT</td>
<td>0.000</td>
</tr>
<tr>
<td>VASC</td>
<td>0.000</td>
</tr>
<tr>
<td>SCL</td>
<td>0.000</td>
</tr>
<tr>
<td>CGAE</td>
<td>0.000</td>
</tr>
<tr>
<td>MH</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Select a question to explore:

- Pyuria: 0.14
- Bacteriuria: 0.17
- Urine Specific Gravity: 0.21
- Symptoms Of Bladder Obstruction: 0.22
- Casts In Urine Sediment: 0.22
- Flank Pain: 0.23
- Urine Sodium: 0.23
- Hematuria: 0.23
- History Of Proteinuria: 0.24
- Skin Intestinal Or Lung Lesions: 0.24
- Strep Infection Within Three Weeks: 0.24
- Recent Surgery Or Trauma: 0.24
- Papilledema: 0.24
- Ischemia Of Extremities Or Aortic Aneurysm: 0.24
- Exposure To Nephrotoxic Drugs: 0.24
- Disturbance In Clotting Mechanism: 0.24
- Jaundice Or Ascites: 0.24
- Transfusion Within One Day: 0.24
- Atrial Fibr Or Recent Mi: 0.24
- History Of Prolonged Hypotension: No

Pyuria

- >30: 0.074
- 5-30: 0.146
- <5: 0.780
Local Sensitivity Analysis

### Acute Renal Failure Program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATN</td>
<td>0.249</td>
</tr>
<tr>
<td>FARF</td>
<td>0.398</td>
</tr>
<tr>
<td>OBST</td>
<td>0.100</td>
</tr>
<tr>
<td>AGN</td>
<td>0.100</td>
</tr>
<tr>
<td>CN</td>
<td>0.020</td>
</tr>
<tr>
<td>HS</td>
<td>0.005</td>
</tr>
<tr>
<td>PYE</td>
<td>0.010</td>
</tr>
<tr>
<td>AE</td>
<td>0.003</td>
</tr>
<tr>
<td>RI</td>
<td>0.002</td>
</tr>
<tr>
<td>RVT</td>
<td>0.002</td>
</tr>
<tr>
<td>VASC</td>
<td>0.050</td>
</tr>
<tr>
<td>SCL</td>
<td>0.002</td>
</tr>
<tr>
<td>CGAE</td>
<td>0.030</td>
</tr>
<tr>
<td>MH</td>
<td>0.030</td>
</tr>
</tbody>
</table>

### Kidney Size

<table>
<thead>
<tr>
<th>Size</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.093</td>
</tr>
<tr>
<td>Normal</td>
<td>0.768</td>
</tr>
<tr>
<td>Large</td>
<td>0.127</td>
</tr>
<tr>
<td>Very Large</td>
<td>0.013</td>
</tr>
</tbody>
</table>

### Commit

Commit 0.95 Dec. Anal.
Case-specific Likelihood Ratios

Acute Fulminant Pyelonephritis W/O Obstr

Pyuria
- >30
- 5-30
- <5

Casts In Urine Sediment
- Wbc
- Hy Gran >8
- Hy Gran 3-8
- Tubular Cell
- None Or Hy Gran 0-2
- Fatty
- Rbc Hb

Bacteriuria
- High Colony Counts
- Sterile

History Of Proteinuria
- Yes
- No

Urine Specific Gravity
- 1.001-1.007
- 1.008-1.018
- >1.018
Therapy Planning Based on Utilities

The following facts are known about this patient:
- Age: Over 70
- Sex: Male
- Blood Pressure At Onset: Moderately Elevated
- Urine Volume: 50-400 Cc Day
- Kidney Size: Large
- Large Fluid Loss Preceding Onset: No
- Proteinuria: Zero
- History Of Prolonged Hypotension: No

This leads to the probability distribution over the diseases:
- ATN: 0.000
- FAF: 0.006
- OBSTRA: 0.956
- AGN: 0.000
- CN: 0.000
- HS: 0.000
- PVE: 0.027
- AE: 0.000
- RI: 0.000
- RUT: 0.000
- URSC: 0.000
- SCL: 0.000
- CAGE: 0.000
- MH: 0.000

Plans for further testing and treatment (in descending value order) are:
- Calculating full plan...
- Determining best plan...

Plan number 1:
- Therapy SURGERY-FOR-URINARY-TRACT-OBSTRUCTION has ev=2862.9 (v=2862.9)

Plan number 2:
- Action RETROGRADE-PVELOGRAPHY, with possible outcomes giving ev=2400.1:
  - Outcome 0 (OBSTRUCTION), with p=0.9569
    Best decision gives ev=2521.8
  - Therapy SURGERY-FOR-URINARY-TRACT-OBSTRUCTION has ev=2621.8 (v=3122.3)
  - Outcome 1 (NO-OBSTRUCTION), with p=0.0431
    Best decision gives ev=2525.9
    Therapy ANTIBIOTICS has ev=2525.9 (v=-1025.3)

Plan number 3:
- Action TRANSFEMORAL-ARTERIOGRAPHY, with possible outcomes giving ev=2361.0:
  - Outcome 0 (CLOT), with p=0.0100
    Best decision gives ev=2359.4
    Therapy SURGERY-FOR-URINARY-TRACT-OBSTRUCTION has ev=2359.4 (v=2861.3)
  - Outcome 1 (NO-CLOT), with p=0.9900
    Best decision gives ev=2351.0
    Therapy SURGERY-FOR-URINARY-TRACT-OBSTRUCTION has ev=2351.0 (v=2862.9)

Plan number 4:
- Action BIOPSY, with possible outcomes giving ev=1862.8:
Assumptions in ARF

• Exhaustive, mutually exclusive set of diseases
• Conditional independence of all questions, tests, and treatments
• Cumulative (additive) disutilities of tests and treatments
• Questions have no modeled disutility, but we choose to minimize the number asked anyway