Galen and Fallot: Computational Diagnostic Models

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Outline

- Introduction
- Galen
  - Data structures
  - Pattern matching
  - Reasoning method (RBR)
- Fallot
  - Data structures and pattern matching
  - Evidence Points metric
  - Knowledge Bases
  - Reasoning Model
- Example
- Summary

Computational Diagnostic Models

- Galen – named for a 2nd century AD Greek physician
  - Known for his model of the circulatory system
- Fallot – named for a 19th century AD French physician Etienne-Louis Fallot
  - Wrote about “la maladie bleue” – causes cyanosis (blue skin tone)
  - One of the most common complex defects
  - Defect named Tetralogy of Fallot (TF) in his honor

Applications

- Pediatric cardiology
  - Identifying congenital heart defects
  - Large prototype knowledge base for Galen and Fallot
- Animal classification
  - Simple rule base for Galen

Pediatric Cardiology

- The diagnosis of congenital heart defects
- Four types of physical defects occur:
  - Holes,
  - Partial obstructions and insufficiencies,
  - Misconnected vessels, and
  - Electromechanical defects (excluded here).
- Physiologic manifestations
  - Hypertrophy – muscle thickening
  - Enlargement – increased chamber size

The Pediatric Cardiology Information Processing Task

Input Data (cues) Output

age sex history
heart EKG
X-ray physical exam
Defect(s) - severity - subtype - location
Physiological states
Support for potential solutions

Reasoner
Galen

- Early 1980s – mid 90s
- Recognition-based reasoning (RBR)
- Based on expert problem-solving behaviors
- Implementations in several Lisp dialects

**Galen Data Structures - Objects**

- Primitive objects
  - Lisp number or symbol
- Contextual objects (not OOP objects)
  - Lisp list with a context symbol first and some number of elements (primitive or contextual) in the rest
    
    \[
    (c \ e_1 \ e_2 \ e_3 \ldots \ e_k) 
    \]

- Hold data of interest
  
  \{
  systolic_murmur
  (location (pulmonary))
  (loudness moderate)
  \}

**Galen Data Structures - Scratchpad**

1. Data – read in
2. Hypotheses – reasoning process

- Format – contextual object
  
  \{
  scratchpad (data)
  (hypotheses)
  \}
Galen Pattern Matching

- Matching data
  - Contexts must be the same
  - Element patterns
    - Identical match
    - Arb – any arbitrary pattern
    - Any – one of several
    - Non – does not contain
    - Opt – optional pattern

Galen Rules

- Simple syntax
  $$\text{(if } \langle \text{patterns} \rangle \text{ then } \langle \text{actions} \rangle)$$

- Example
  $$\text{(if} \quad (s2 \ (\text{single})) \quad \text{then} \quad (\text{propose} \quad \text{tetralogy\ of\ fallot}))$$

Galen Reasoning Cycle

- Repeat:
  1. Enter new data
  2. Proposer – use proposer rules (knowledge base) to activate relevant hypotheses
  3. Reviewer – use reviewer rules (KB) to review all active hypotheses
- Until out of data
- Print summary

Galen Hypothesis States & Actions

- Propose – activated, added to scratchpad hypothesis page
  - Once activated, a hypothesis may be confirmed, opposed, accepted and rejected,
- Accept – believed true
  - Confirm or oppose do not change state
  - If believed false, must be rejected
  - At end_of_data, Accepted hypotheses
- Reject – believed false (terminal)
  - Terminal action – can’t transition again (even if an accept rule is found)
- Confirm – positive evidence
  - Post evidence, may be enough to accept
- Oppose – negative evidence
  - Terminal action _ no further
  - Post evidence, may be enough to accept

Goals of Recognition-Based Reasoning (RBR)

- Recognize (named) defect
- make good
- conclude
- determine defect type and severity
- reject defect
- find critical evidence
- evaluate evidence
- + cues/states
- - cues/states
Code --- Part I --- Galen Kernel

```lisp
;; Initialize "Galen/Fallon" ; Initialize Galen & Fallon
c:\\nreed\\fallot\\
;; in a specific directory...
;; SITE DEPENDENT
;; by loading each file.
"macrofun" ;; First: global parameters, core macros
;; and functions.
;; then Galen modules
"dewey" ;; Operate on Dewey Decimal numbers
"objects" ;; Operations on Galen Objects
"read" ;; Read things from the terminal
"write" ;; Write things to the terminal
```

Code --- Part II --- Galen

```lisp
;; then load the rest (in alphabetical order)
"canned" ;; Store & retrieve canned problems
"consequents" ;; Production rule consequents
"define" ;; Functions to set up a knowledge base
"general" ;; General methods including Proposer & Reviewer
"locate" ;; Locative pattern matcher.
"main" ;; Main program for Galen incl prelude and postlude.
"questions" ;; Ask questions from a menu object
"reflect" ;; Reflective pattern matcher
"rules" ;; The rule interpreter
"scratchpad" ;; Define the scratchpad
"wellform" ;; Check objects for well formedness
```

Code --- Part III --- Fallot

```lisp
;; now load the Fallot specific files
"support" ;; FALLOT globals and cue combination
functions
"fallot-main" ;; FALLOT main, control, and general
functions
"specific" ;; FALLOT cue combination and points
calculation functions
;; Test (domain) specific methods
"auscult" ;; FALLOT Auscultation method functions
"physexam" ;; FALLOT Physical exam method functions
"ekg" ;; FALLOT EKG method functions.
"x-ray" ;; FALLOT Xray method functions
;; experimental functions for weights on cues
"weights" ;; Test variable weights
```

The Fallot Computational Model

- Early 1990s – present
- Heuristic solution construction and evaluation
- Models interactions between defects to diagnose multiple defect cases
- Common Lisp implementation
- A focus on diagnostically relevant data
- Based on expert reasoning strategies
- Recognition-based reasoning is used on named (single or complex) defects
- Evaluation (test-specific) methods with knowledge of how cues combine are used on interacting defects

Fallot Data Structures & Modules

```
# Fallot Data Structures & Modules

Abstract features
Support structure

Recognize defects
Identify features
Construct solutions
Evaluate solutions
Test-specific methods

Recognize defects
Cover cues
Associated defects
Eliminate incompatible defects
Eliminate duplicates

General methods
```

Reasoning Cycle of Fallot

Repeat
1. Input new cue(s) G
2. Find applicable methods G + F
3. Apply methods G + F

Until out of cues
4. Summarize active hypotheses G + F
5. Evaluate current solution (if any) F
While no adequate solution has been found
6. Construct candidate solutions F
7. Evaluate candidate solutions F
End while
8. Summarize solutions F
Fallot Goal Structure/Task Decomposition

- Find plausible diagnoses
  - Identify features
  - Recognize defect
  - Construct and evaluate potential solutions
    - Test 1 (heart)
    - Test N-1 (EKG)
    - Test 2 (X-ray)
  - Evaluate solutions

Comparing Alternative Solutions
- A case (C) produces a set of observed cues
  - normal (expected of an average healthy patient)
  - abnormal
- A set of defects is a potential solution (S) that have expected cues
  - normal
  - abnormal (always present)
  - optional abnormal
  - Matching with single defect S, cue combination with multiple defect S

Evidence Points Metric
- Most significant abnormal observed (C) and expected (S) cues
  - If explained - positive support for S
  - If not - negative support for S
- “ignore” normal cues
  - “Neutral” support for S

\[
\text{Explanation Points}(C,S) = \frac{\sum \text{Explained Abnormals} (\text{Observations}(C)\text{or Expectations}(S))}{\sum \text{Explained Abnormals} + \sum \text{Unexplained Abnormals}}
\]

EP -- Cluster Cues by Type

Example not explained:
- Observed X (C)
  - soft
- Expected X (S=D1)
  - (D1) normal

Examples explained:
- Observed X (C)
  - soft
- Expected X (S=D2)
  - (D2) soft
- Observed X (C)
  - soft
- Expected X (S=D1 and D2)
  - (D2) soft, (D1) normal
- Observed X (C)
  - normal
- Expected X (S=D2 and D3)
  - (D2) soft, (D3) loud

Constructing solutions
- Heuristic solution construction
  - Abnormal observed cues “trigger” defects.
  - Features of the case restrict solutions.
  - Consider frequently co-occurring defects with primary defects (interactions may mask).
- Exhaustive search - test all possible solutions.

Defect association frequencies
When one defect may be present, other defects that are:
- **commonly** associated,
- **occasionally** associated, or
- **rarely** associated

with that defect may also be present.
Defects that are **never** associated cannot be present.
7 defects investigated

- AS - Aortic Stenosis (obstruction).
- PS - Pulmonary Stenosis (obstruction).
- ASD - Atrial Septal Defect (hole).
- VSD - Ventricular Septal Defect (hole).
- PAPVC - Partial Anomalous Pulmonary Venous Connection (mis-connection).
- TAPVC - Total APVC (mis-connection + hole).
- TF - Tetralogy of Fallot (hole + obstruction).

VSD – ventricular septal defect, hole between ventricles
PS – pulmonary stenosis, blockage around pulmonary valve
LVH – left ventricular hypertrophy, increased muscle thickness
Aorta overrides the VSD

Heuristic Solution Construction

1. Construct candidate 1-defect solutions using
   1 - essential, 2 - accepted, then 3 - proposed defects.
2. Construct n-defect solutions (n up to Maximum / Solution)
   To each candidate (n-1)-defect solution, add
   1 - essential, 2 - accepted, 3 - proposed defects,
   then 4 - associated defects
   (common, occasional, rare).
   Remove duplicate solutions.
   Remove solutions of incompatible types.
   Remove solutions with incompatible defects.

Example Case with Multiple Defects

- Case WB75
  - Defects
    - Aortic Stenosis (AS) - blockage
    - Atrial Septal Defect (ASD) - hole
  - Defects interact
  - Data menu
    - user selects choices and enters numbers
    - Data saved in contextual object format
    - Unit conversions on input

Case Data I

```plaintext
{wb75
  {age 60.0
  {sex male
  {when_recognized
  {age_when_recognized 0
  {reason_for_recognition murmur
  {present_symptoms
  {frequency_of Resp_infections {less_than_6_per_year}}
  {gestation
  {weight 8.867842}
  {physical_examination
  {height 42.125984
  {weight 38.21586
  {blood_pressure
  {right_arm {systolic 100} {diastolic 72}
  {leg {systolic 100} {diastolic 76}}
  {pulse 90
  {respirations 20}
  {heart {location_of_cardiac_apex {intracostal_space 5lics}}
  {thoracic {neck}}
  {abdominal}
  {systolic_murmur
  {location {pulmonary_area}}
  {loudness 5}
  {time_ejection
  {radiation_back}}
  {s1 normal}
  {s2 (normal)}
  {sec_apex}
  {ekg
  {axis {deviation_right}}
  {x-ray
  {pulmonary_vasculature
  {abnormal {pulmonary_arterial_markings increased}}
  {cardiac_size mildly_enlarged}}
  (end_of_data))
```
Interactions --
Murmurs and Sound S2

- Murmurs: *Louder* ones mask *softer* ones occurring at the same time within the heart cycle (*ordered dominance*).
- S2: width (between 2 parts of the sound) combines *additively*. *Narrow, normal, wide*.
- S2: width on inspiration combines *additively*. *Variable or fixed*.

Example interactions

\[ \text{AS} \rightarrow \text{moderate aortic systolic ejection murmur} \rightarrow \text{ASD} \]

\[ \text{ASD} \rightarrow \text{loud pulmonary systolic ejection murmur} \rightarrow \text{AS} \]

\[ \text{ASD} \rightarrow \text{wide, fixed, split S2} \rightarrow \text{ASD} \]

\[ \text{AS} \rightarrow \text{narrow, variable split S2} \rightarrow \text{AS + ASD} \]

Evidence Points - Auscultation

<table>
<thead>
<tr>
<th>Cue type</th>
<th>AS (matching)</th>
<th>ASD (HSC)</th>
<th>ASD + AS</th>
<th>ASD+AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murmurs</td>
<td>0 / 2</td>
<td>1 / 1</td>
<td>1 / 2</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Thrills</td>
<td>1 / 2</td>
<td>1 / 2</td>
<td>2 / 2</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Clicks</td>
<td>1 / 1</td>
<td>0 / 1</td>
<td>1 / 1</td>
<td>1 / 1</td>
</tr>
<tr>
<td>Sounds</td>
<td>0 / 1</td>
<td>0 / 1</td>
<td>0 / 1</td>
<td>1 / 1</td>
</tr>
<tr>
<td>Total</td>
<td>2 / 6</td>
<td>2 / 5</td>
<td>4 / 6</td>
<td>6 / 6</td>
</tr>
</tbody>
</table>

Total Evidence Points on Case WB75

<table>
<thead>
<tr>
<th>Cue type</th>
<th>AS</th>
<th>ASD</th>
<th>ASD and AS (matching)</th>
<th>ASD+AS (Fallot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auscultaion</td>
<td>2 / 6</td>
<td>2 / 5</td>
<td>4 / 6</td>
<td>6 / 6</td>
</tr>
<tr>
<td>EKG</td>
<td>0 / 1</td>
<td>1 / 1</td>
<td>1 / 1</td>
<td>1 / 1</td>
</tr>
<tr>
<td>Physical</td>
<td>0 / 0</td>
<td>0 / 0</td>
<td>0 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td>X-ray</td>
<td>0 / 2</td>
<td>2 / 2</td>
<td>2 / 2</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Total</td>
<td>2 / 9</td>
<td>5 / 8</td>
<td>7 / 9</td>
<td>9 / 9</td>
</tr>
</tbody>
</table>

Summary of solutions explored

Best solutions (>70%)

- **AS+ASD** 9/9 (correct solution)
- **AS+PS** 8/10
- **PS+ASD** 8/10
- **ASD+PAPVC** 8/10
- **ASD+TF** 8/10
- **PS+VSD** 7/10

Other solutions explored

- **AS** 2/9
- **PS** 3/9
- **ASD** 5/8
- **ASD+VSD** 6/9
- **AS+VSD** 6/10

Output on Case WB75

wb75out99.txt
Current Work
- Finding more cases
- Additional domain(s)
- Different weights in EP metric for different types of cues
- Automated processing of input data starting with phonocardiograms (PCGs) from an electronic stethoscope

Summary
- Two related computational models, Galen and Fallot
- Lisp implementations meant easy integration of multiple diagnostic reasoning modes
- Current work enhancing the models

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