Fuzzy Diagnosis using Order of Magnitude Exaggeration

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Overview

- Motivation (UAV fuel system) & background
  - FMEA/Bayesian fault detection and diagnosis
  - Orders of magnitude representation
  - Qualitative symptom generation
- Fuzzy symptom interpretation
- Exaggeration reasoning/faults
- Example
- Conclusions

2/7. Building a fault diagnosis model
FMEA

BAE SYSTEMS

Our task was to replace the manual FMEA with an automated one

Failure modes and effect analysis (FMEA)

- **Extended to obtain crude measures of**
  - **Fault prior probabilities**
  - **Symptom observation given single fault conditional probabilities**

Fault	Chance of fault	**Symptom**	Chance of …ymptom …rvation
Valve Jammed Closed	0.01	When valve commande… sensor reports closed	[illegible]
		When pump commanded, low pressure detected	0.6

? thresholding

? engineer expert

(Slide courtesy of R. Bovey BAE)

Background #1

- Qualitative symptoms are produced from an automated FMEA. [N. Snooke, C. J Price, Automated FMEA Based Diagnostic Symptom Generation, *Advanced Engineering Informatics,* AEI 2012, Vol. 26, pp. 870-888.]
  - Developed for a BAE Systems Bayesian network diagnosis system
- Unlike a manual FMEA our symptoms are state specific (necessary state is included in the symptom)
  - given fault, its (valid) symptoms *will* be present.
  - so we don't need to encode expert knowledge as the *probability* of a symptom being observed given existence of fault
  - rather the knowledge comes from the models and simulation (but more produces more complex symptoms)

Background #2

- The underlying simulation allows magnitude separation of phenomena. [N. A. Snooke. Qualitative Order of Magnitude Energy-flow Based Failure Modes and Effects Analysis. *Journal of Artificial Intelligence Research*, 46:413–447, 2013]

  - e.g. mΩ, Ω, KΩ, MΩ, ...
  - e.g. mS, S, H, Day, Year, ...

  - The simulation assumes that *n* is small enough that:

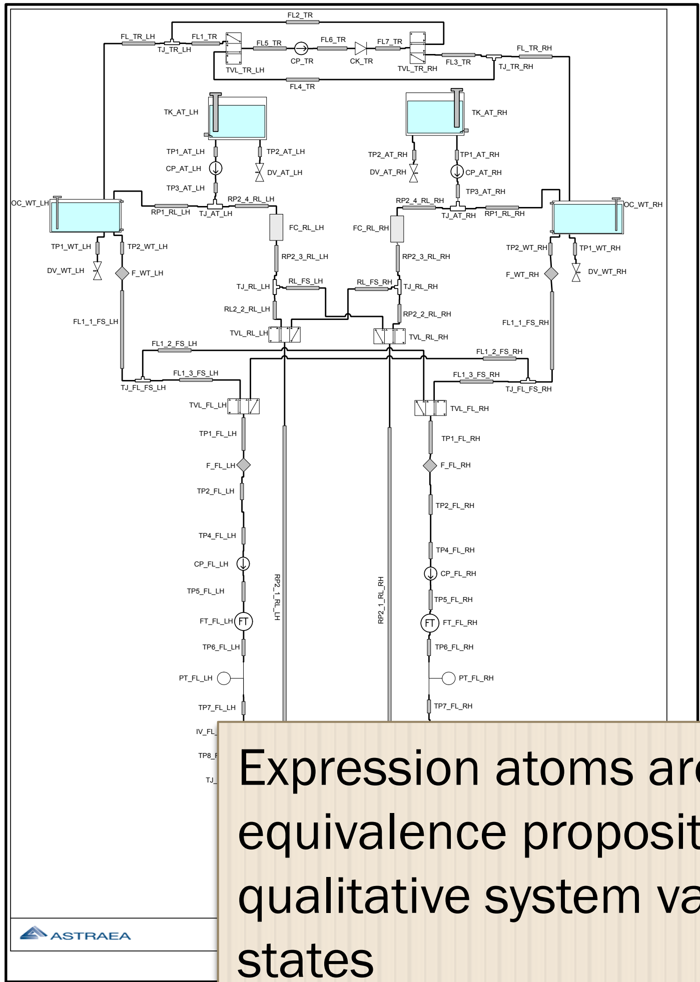
$$nr^{\rhd a} \gg r^{\rhd (a+1)}$$

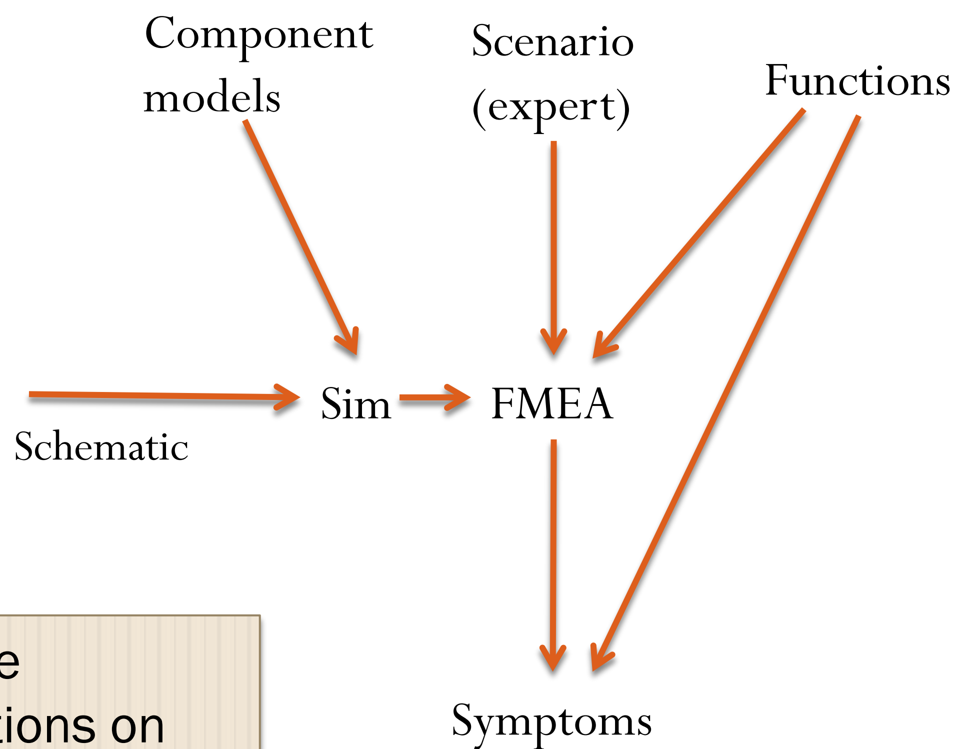
  - Where $r^{\rhd a}$ is a orders of magnitude less than r.

Qualitative Orders of Magnitude

- Supports significant nominal distinctions
- Supports exaggeration of faults
  - To produce an exaggerated effect that has qualitative value significance.
  - Weld[see later slides] proposed the idea in 1990 and utilised a qualitative magnitude space based on hyperreals by including *negligible* and *infinity* into the qualitative {-,0,+} space.
- Each OM level is *negligible* w.r.t. the next higher OM

Symptom generation





Expression atoms are equivalence propositions on qualitative system variables or states

when SYSTEM_ON
if B == NORMAL AND C == LOW
implicates FAULTX, FAULTY

Symptom rules

- A symptom is Boolean expression (fuzzy rule antecedent) and a set of implicated faults (fuzzy rule consequent)

$$S = (E, F)$$
$$F = \{M_1, M_2, ...\}$$

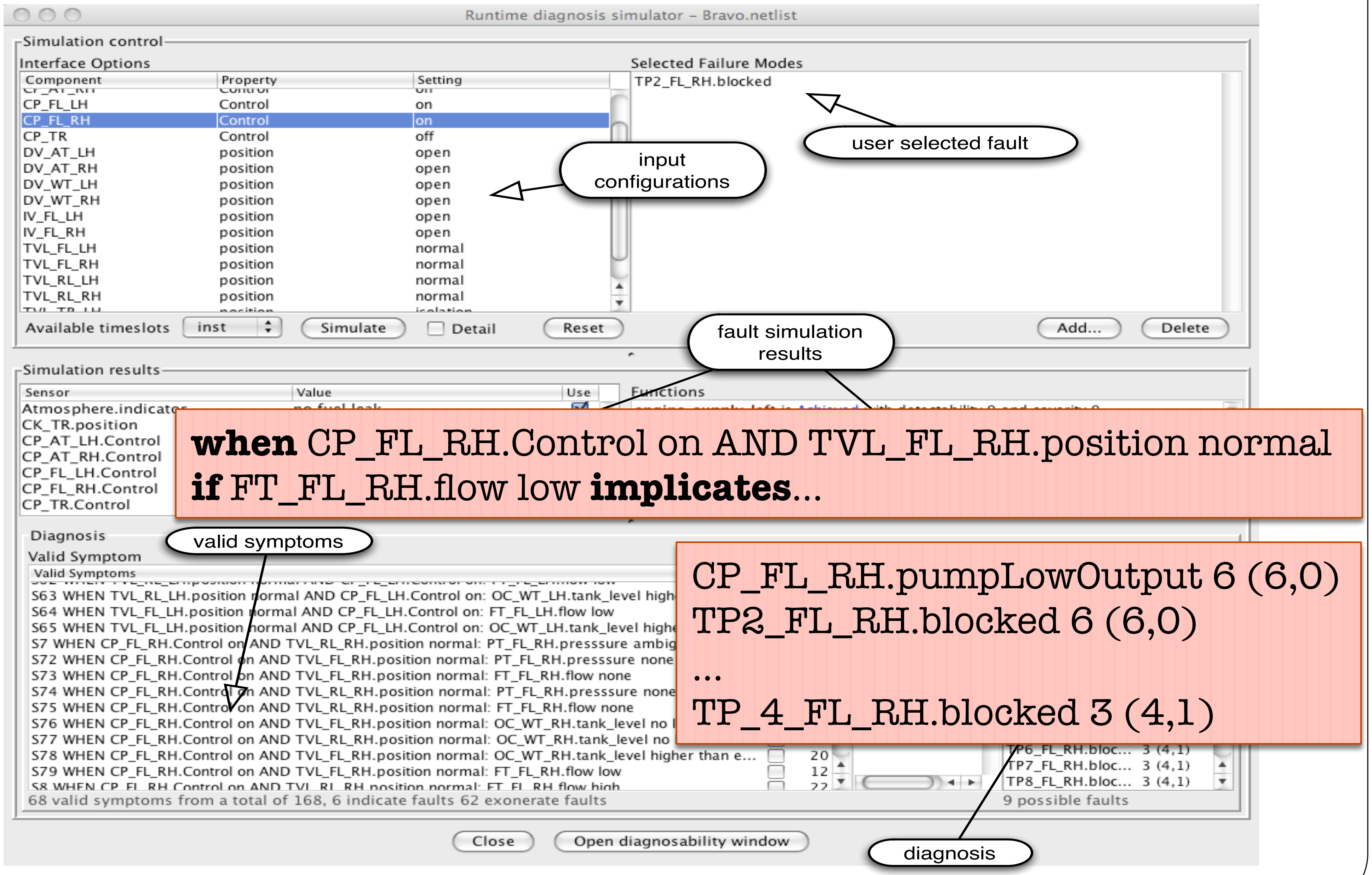
- The expression contains two parts

$$(E_c, E_o)$$

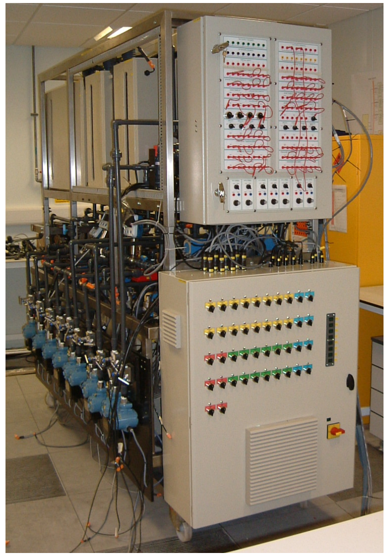
- To allow exoneration:

$$(E_c \wedge E_o) \text{ implies } \{M_1, ...\}$$
$$(E_c \wedge \neg E_o) \text{ implies } \{\neg M_1, \neg ...\}$$
$$\neg E_c \text{ rule invalid}$$

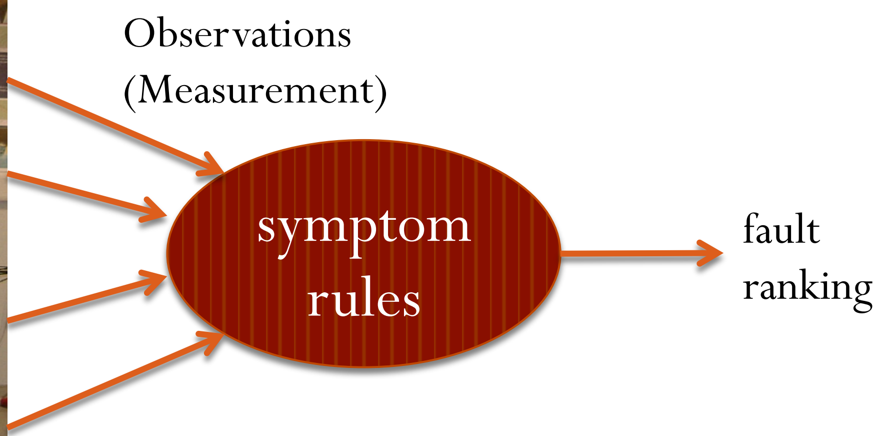
Symptom based fault detection



Runtime fault detection/ diagnosis

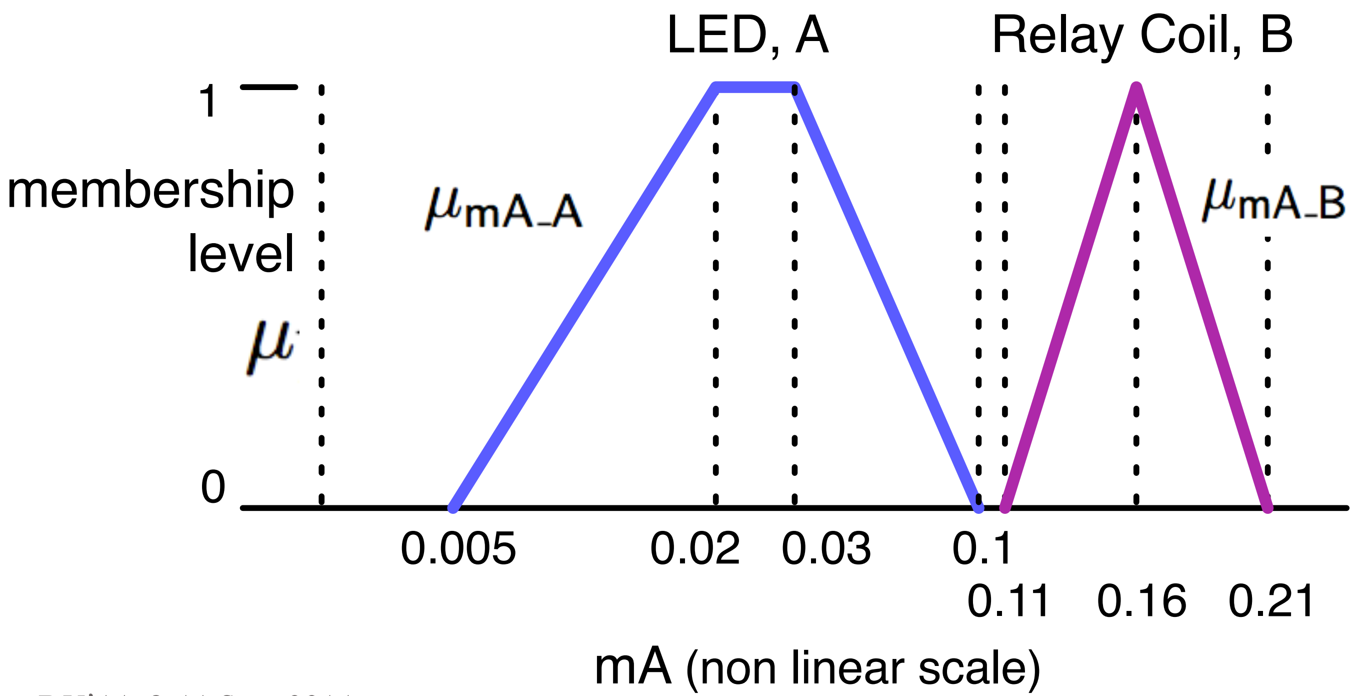


- To use these qualitative symptoms for fault detection we need to interpret numerical measurements using the qualitative rules



Fuzzy Sets (to avoid thresholding)

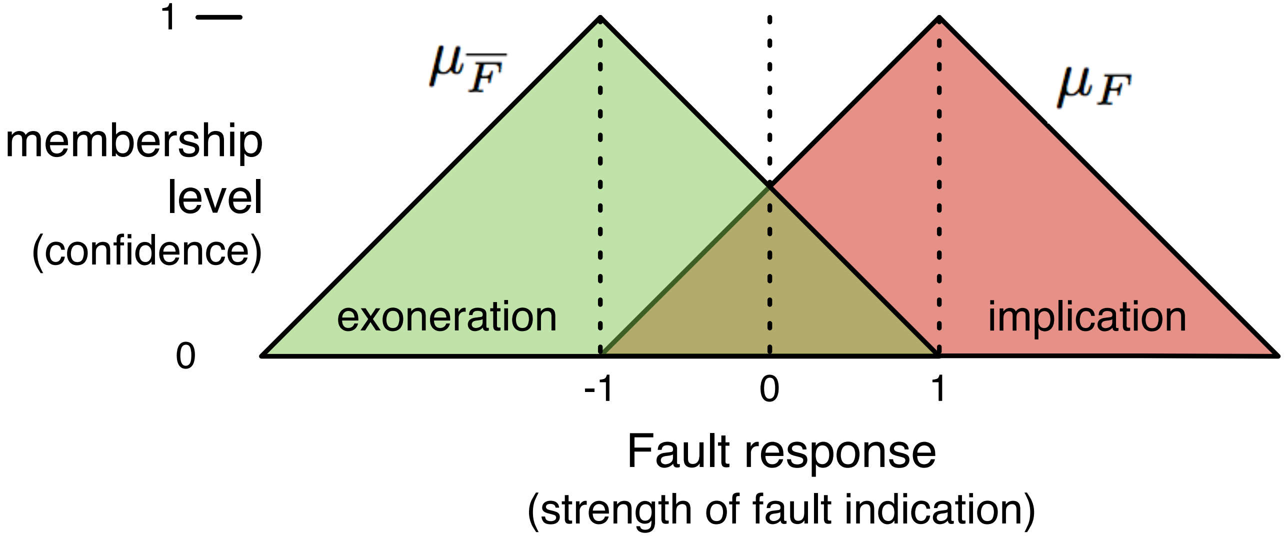
- Provide a degree of membership to a set defined on some domain. E.g. qualitative signal level current:
- E.g if LED.current==mA …



A = 1[0.02, 0.03, 0.015, 0.07]

Fault (rule consequent sets)

- Fault response domain

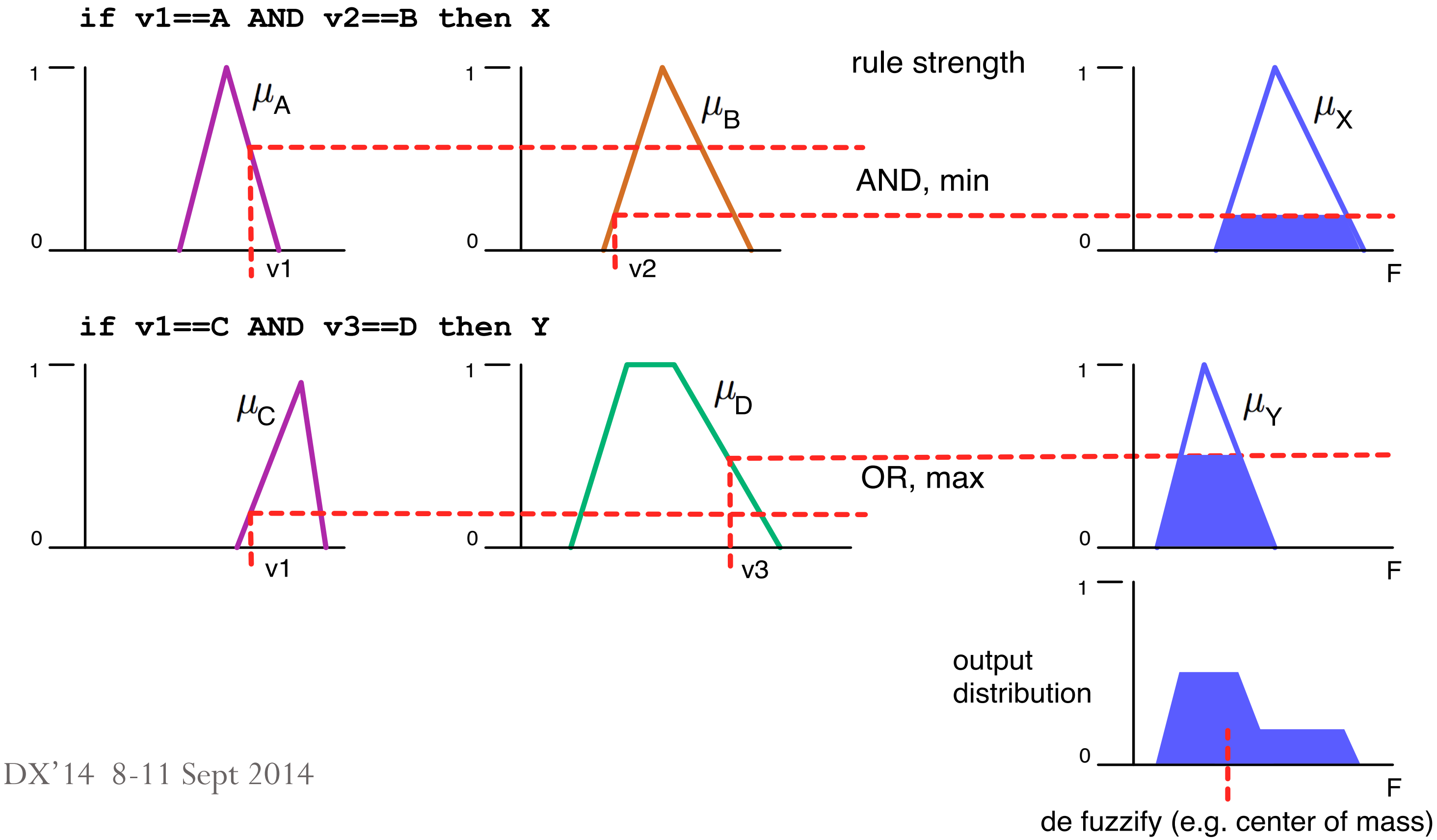


- -1 fully exonerate fault
- 0 contradictory evidence of fault
- 1 fully implicate fault

Basic fuzzy inference (bookwork)

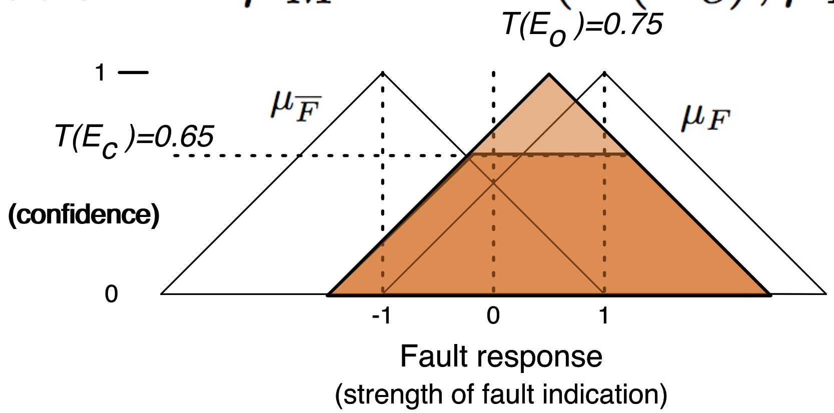
- Zadeh operators: $\mu_{A \cap B}(x) = min[\mu_A(x), \mu_B(x)]$
  $\mu_{A \cup B}(x) = max[\mu_A(x), \mu_B(x)]$

- Mamdani inference (aggregate clipped output sets)



Symptom Inference

- Determine truth value for $T(E_c)$ and $T(E_o)$
- The consequent set is *generated* from $T(E_o)$, which represents the level of fault implication based on the observation membership strength:
  $$\mu_{E_o} = [2(T(E_o) - 1), 2(T(E_o) - 1), 2, 2]$$
- Clip the consequent set according to the truth value of the antecedent: $\mu_M = \min(T(E_c), \mu_{E_o})$



Symptom Inference

- Good for nominal operation rules:

  when SYSTEM_ON
  if pump.v==V AND output_flow==normal
  implicates no_fault

  Where V and normal are OM qualitative values

- But what about faults?
  - to provide qualitatively significant effects…
  - our faults and effects are (OM) extreme
  - worst case effect is good for FMEA
  - *but we need the fault to be detected progressively*

Exaggeration

- "Instead of tracing the effect of a perturbation through the causal structure of the system, exaggeration considers the behavior of a system in which the perturbation is taken to a limiting value. If this new system has a qualitatively different behavior from the original, then exaggeration postulates a general trend caused by the perturbation." (Daniel S. Weld. Exaggeration. *Artificial Intelligence*, 43(3):311 – 368, 1990)

- increased -> ∞;
- decreased -> *negligible*

Exaggeration: heat exchanger [Weld]

- E.g. what happens to the output temperature of a heat exchanger if the fluid flow rate increases?

- Exaggeration:
  - **If** the fluid flow was infinite, the oil would spend negligible time in the exchanger. Since the rate of cooling is finite, the oil would lose negligible heat and exit hotter than oil moving at finite speed. *Thus any increase in oil flow rate will cause a corresponding increase in output temperature*.

vs.

- Propagate perturbation through model:
  - Since the rate of cooling is dependent only on the initial temperature and thermal conductivity and these are unchanged, the rate of cooling is unchanged as a function of time. Since the oil will spend less time in the pipe, it will exit with a higher temperature.

Exaggeration steps

- Transform
  - Exaggerated faults
  - E.g. *leak fault* flow OM larger than nominal flow
    - Modelled with an OM low resistance connection to atmosphere
- Simulate
  - Using values (not differences/perturbations)
- Scale
  - Provided by the fuzzy set used to interpret real observations for the qualitative rules.

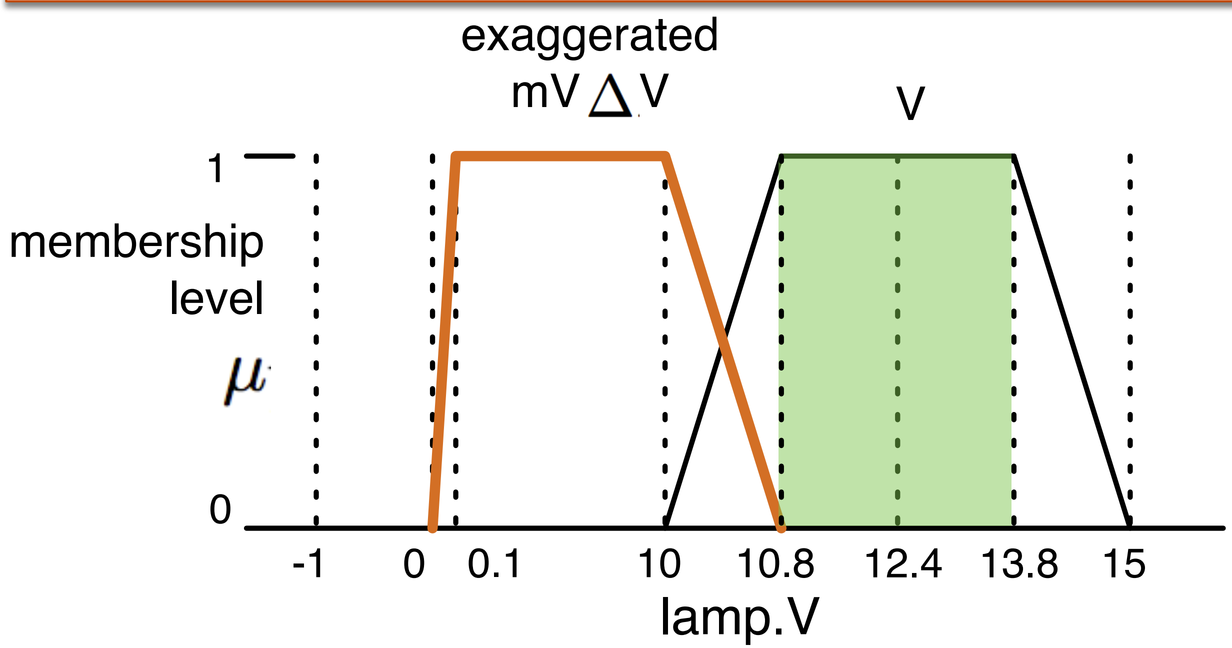
- Not guaranteed to produce a correct result if the system does not respond monotonically to the exaggeration.

What does the fuzzy set for abnormal values look like?

Fuzzy Exaggeration

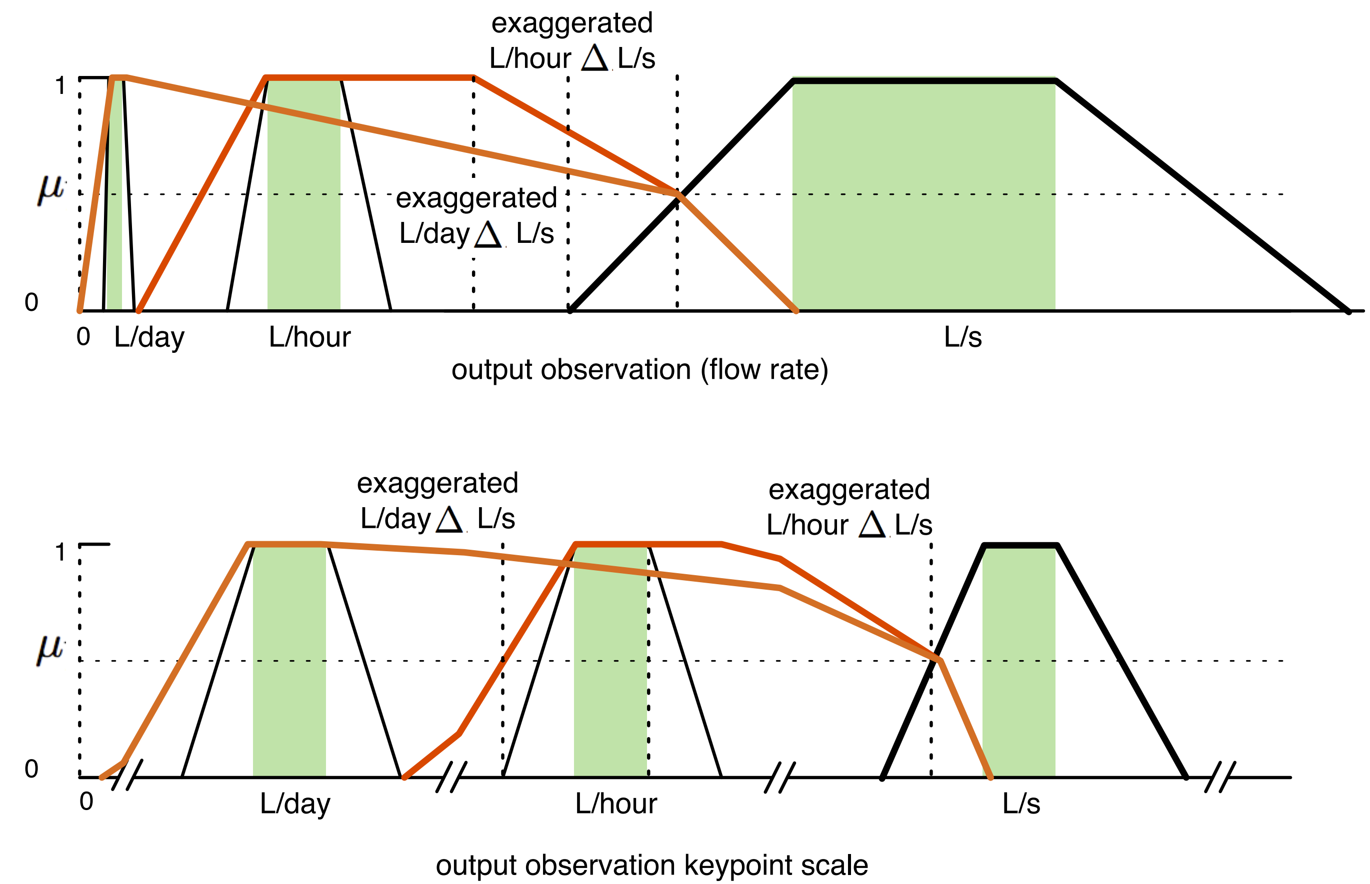
- Symptoms contain `abnormal measurement' atoms
- Fuzzy set scales the effects of a resulting simulation.

when … **if** lamp.V==mVΔV **implicates** corroded_connection



Progressive scaling

- Fits with the OM idea to support parameterized faults.

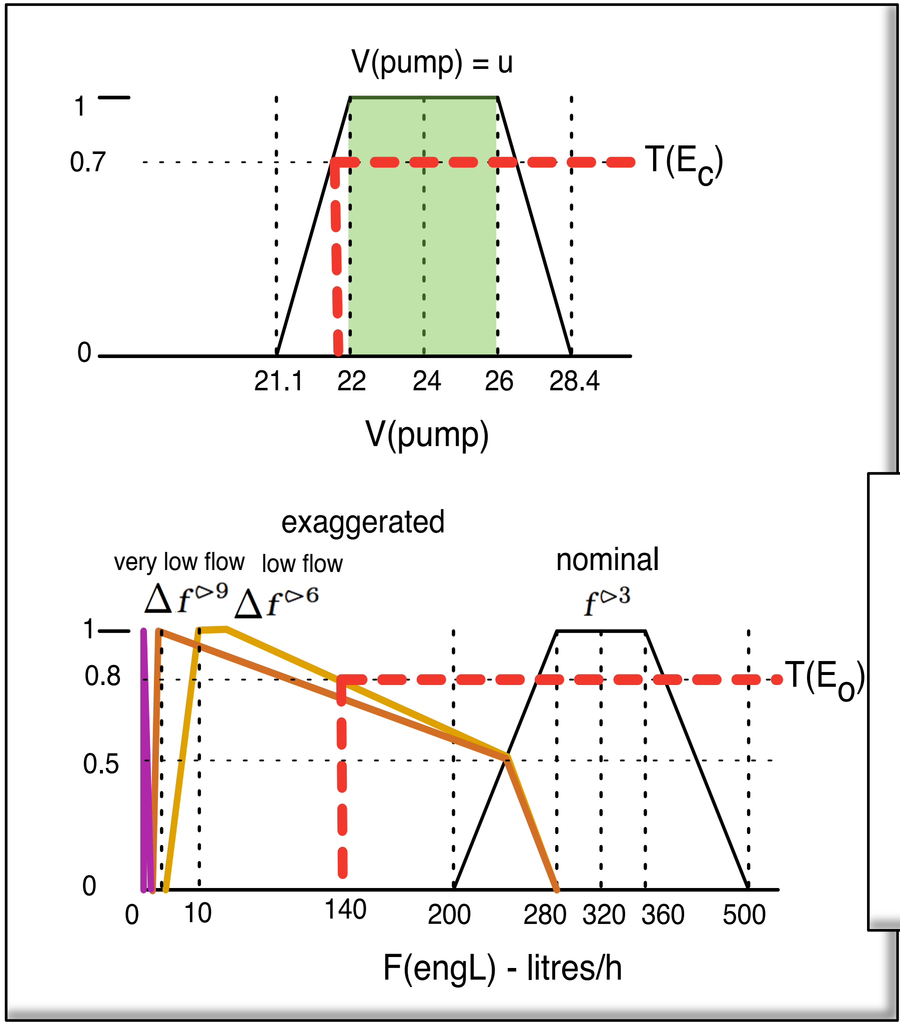


Example: symptom interpretation

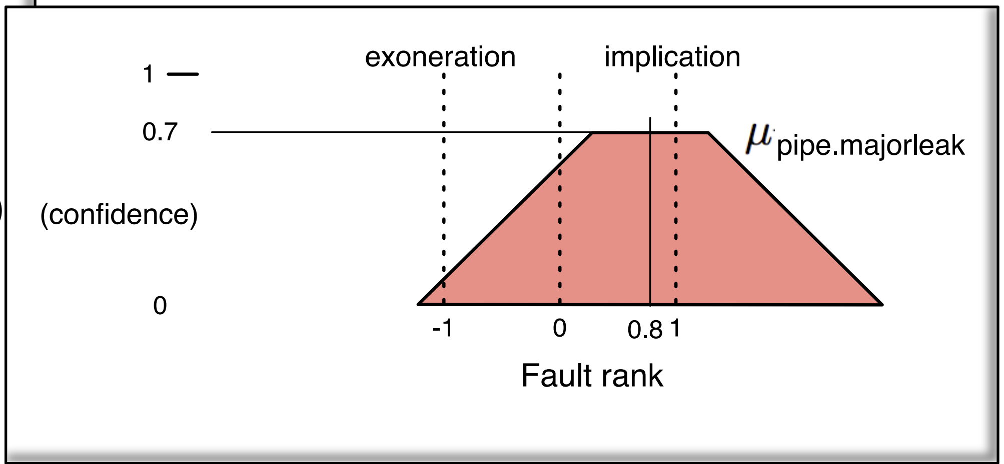
- Consider a symptom:

$$\begin{aligned} \text{S1 : when} \quad & V(\text{pump}) \leftrightarrow u \\ \text{if} \quad & F(\text{engL}) \leftrightarrow f^{\rhd 6} \Delta f^{\rhd 3} \\ \text{implicates} \quad & \{\text{pipe.majorleak}, \text{impeller.binding} \wedge \text{pipeleak}\} \end{aligned}$$

- $f^{\rhd 6} \Delta f^{\rhd 3}$ is a set from the fuel flow domain.
  - a flow of $f^{\rhd 6}$ occurs when $f^{\rhd 3}$ is expected.
  - produced as a failure mode effect in the FMEA.

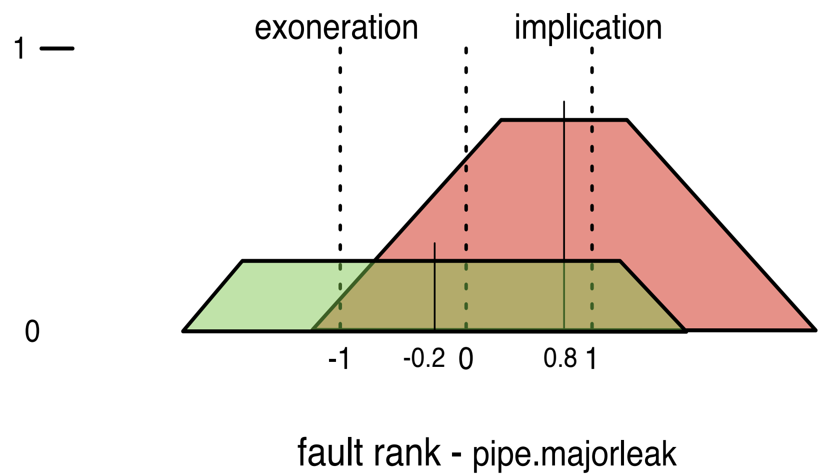


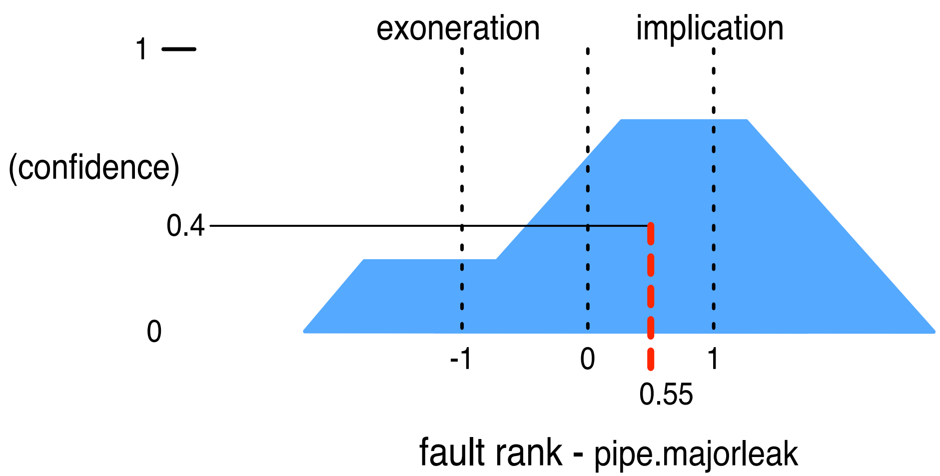
- Observe V(pump) at 21.8V
- Observe F(engL) at 140L/min
- So $T(E_c) = 0.7$; $T(E_o) = 0.8$



Multiple rule inference

- Usually there are multiple indications/contra indications
- Accumulate fault sets
- Defuzzify fault domain
  - E.g. using CoG





Conclusions

- The fuzzy mapping provides a relatively intuitive way to identify operating ranges (pragmatic)
  - interpolates the control points specified by the rules
  - allowing `canned' symptoms to produce a very lightweight diagnostic system (fault detection)
  - symptoms are generated with no additional information beyond the qualitative and functional models used for FMEA

- Exaggeration reasoning is commonly used by humans and has some formalism provided by Weld.
  - to allow exaggerated effects to be scaled back to match actual observations.
  - FMEA provides comparative observation values in symptoms so scaling can be specific to each OM {observed, expected} pair (per component or rule if required)

Conclusions

- An undergraduate student project provided promising empirical results (using a spice based numerical simulator)
- Questions/comments/observations ?

Why this approach?

- Rules (symptom) production is automated (~few hours)
- Rule execution is computationally fast
- Only qualitative fault models required
- Validation of rules
- Manual rules can be inserted if required
  - Specialist knowledge/domain
- FMEA provides representative coverage of operating modes
  - Rules extrapolated using function-structure inferences
  - Symptoms are as general as possible within the coverage of the FMEA encountered states.