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Presented to:
International System Safety Society

Software Risk Assessment: Fuzzy Logic Approach to Risk Estimation (FLARE)

AMRDEC

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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FLARE Outline

- Introduction
  - Problem Statement
  - Proposed Solution
- Fuzzy Logic Approach to Risk Estimation (FLARE)
- Using FLARE
  - Scoring Objectives
  - Processing Scores
  - Estimating Risk Possibility
- Summary

FLARE Introduction

- Standard hardware and operations risk assessments include both the hazard severity and the mishap event likelihood
- However, a widely accepted process for estimating software "risk" is not a standard activity in system level risk assessments
- Predicting system level risk in terms of the composite of hardware, operations, and software risks is a desirable, but difficult objective, given the vagaries of a software risk assessment
- This presentation proposes a fuzzy logic based approach to address the software risk assessment deficiency in the system level risk assessment.

FLARE
Problem Statement

- Assessing hazard severity in linguistic terms (*e.g.* catastrophic, critical, etc.) is a straightforward activity, however, estimating the likelihood of a software safety failure is not a trivial process

- Therefore, the typical software safety assessment is evidence/artifact driven and it's results reflect the analyst's confidence or belief in the "goodness" of the software's safety characteristics relating to software failures

- In other words, most software safety assessments are based on individual decisions analysts make

- The analyst's confidence or "belief" is the basis for estimating software safety risk

FLARE
Problem Statement

- The Software System Safety discipline has adopted a safety assessment process for analysts that use both software hazard analysis objectives and software development objectives

- These two sets of objectives are designed to reduce the likelihood of software safety failures

- The objective produce the analyst's primary evidence/artifacts and they are used to increase/decrease the analyst's belief that the software has reduced/increased likelihood of failure

- The problem with this process is the absence of an estimate for the likelihood of software safety failures and the difficulty of combining software "risk" with hardware/operations risk estimates

FLARE
Problem Statement

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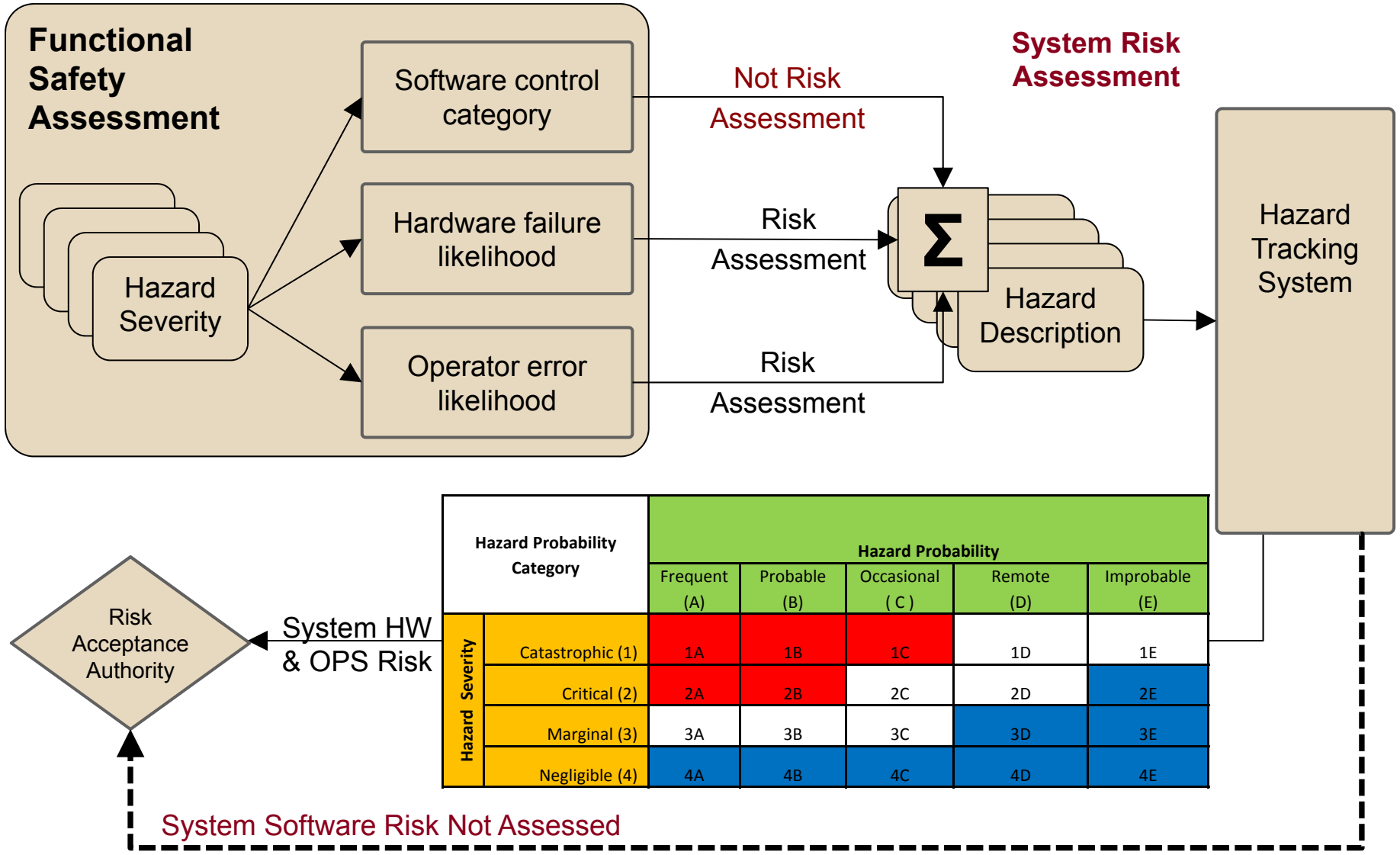

Hazard Probability Category		Hazard Probability				
		Frequent (A)	Probable (B)	Occasional (C)	Remote (D)	Improbable (E)
Hazard Severity	Catastrophic (1)	1A	1B	1C	1D	1E
	Critical (2)	2A	2B	2C	2D	2E
	Marginal (3)	3A	3B	3C	3D	3E
	Negligible (4)	4A	4B	4C	4D	4E

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FLARE
Proposed Solution

- The software safety assessment process is best described as qualitative and the assessment results derive from the analyst's cognition.

- The challenge, therefore, was to formalize a generalized process which maps the analyst's cognition, as it relates to "belief" in software safety assurance, to bounded likelihood categories (not discrete numeric estimates)

- An advantage of the process would allow the likelihood of a software safety failure event to be described in familiar linguistic terms such as "frequent", "occasional", or "improbable".

FLARE
Proposed Solution

- The proposed process is a “next step” toward maturing the software safety assessment process that provides a best estimate of the qualified software contribution to the system level risk.

- Since the current approach to software safety assessment includes the same severity component used in HW and Ops, our “goal” is to qualitatively represent the “likelihood” of a software safety failure in order to better estimate the software’s contribution to system level risk.

- This presentation describes a qualitative fuzzy logic approach for estimating the likelihood of software safety failures.

FLARE
Problem Statement

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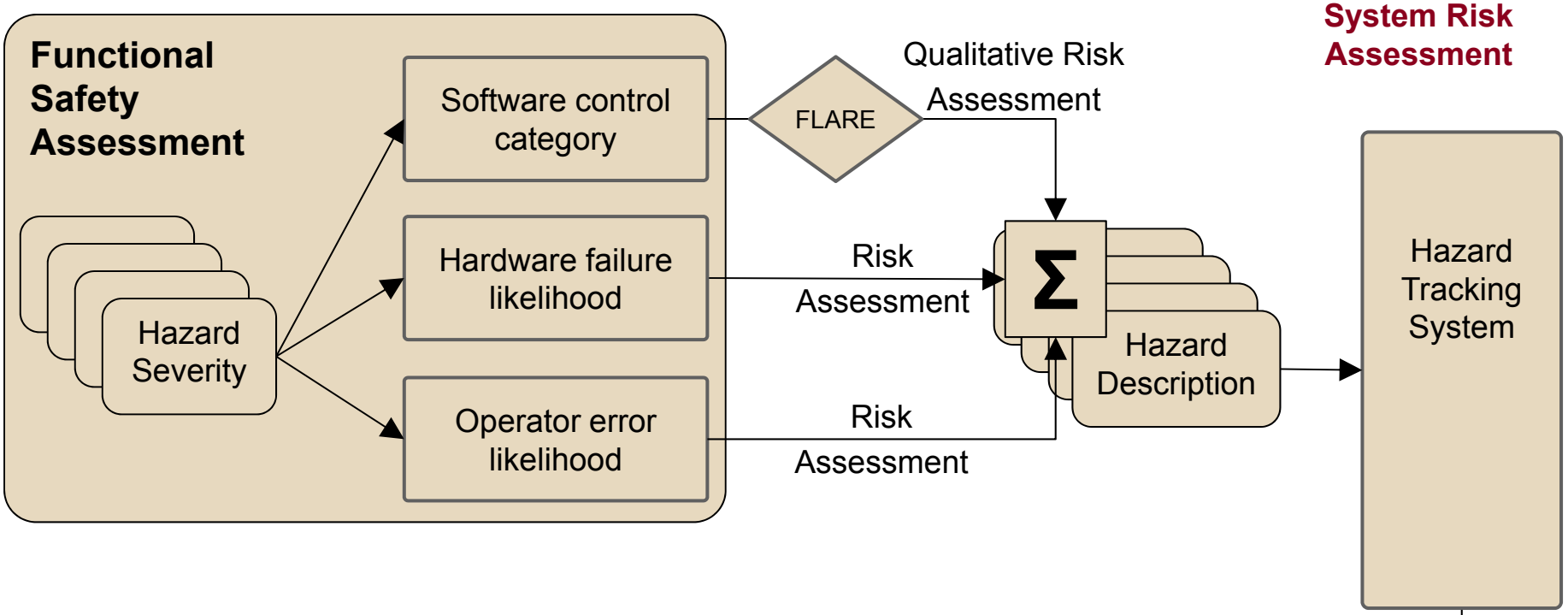
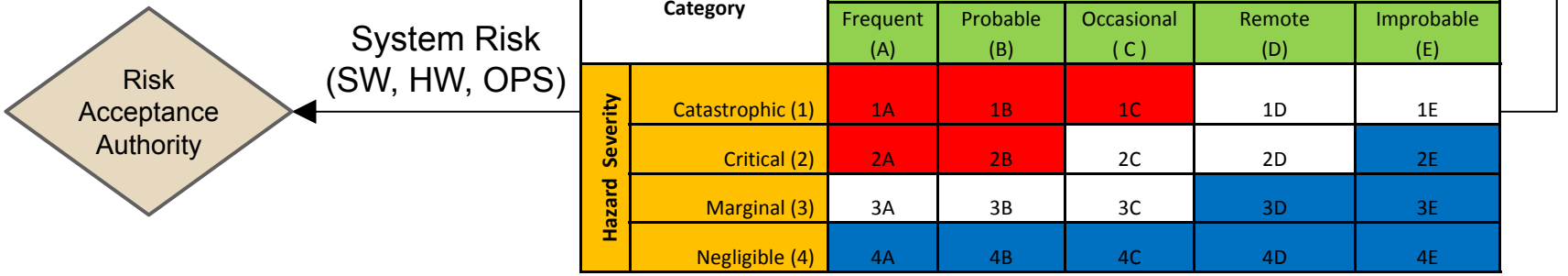
System Risk Assessment





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Fuzzy Logic Approach to Risk Estimation (FLARE) DRAFT

- Fuzzy numbers represent a possibility distribution over a real number line.
- Possibility distributions capture what is possible versus what is probable.
- However, in cases where probability is not available, possibility theory offers a framework to model the data limitations and manipulate them to develop boundaries for decisions.
- FLARE employs fuzzy numbers to model the analyst's beliefs.
- These fuzzy numbers are manipulated by fuzzy logic to arrive at bounded decisions.
- The FLARE process does not "magically" provide "good" decisions from an imperfect data set, merely traceable possibility boundaries.

Fuzzy Logic Approach to Risk Estimation (FLARE) DRAFT

- Fuzzy logic concepts and operations employed in FLARE help to characterize and manage the qualitative characteristics found in software safety assessments.

- The FLARE process associates qualitative belief in software safety assurance to a Software Risk Possibility (SRP) matrix.

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- FLARE provides a method for “assessment of confidence” by the analyst for each safety-significant requirement and function as required by MIL-STD-882E

- Confidence in this context is not the same as mathematical confidence interval Here, it is a qualitative measure of analyst “belief” that satisfactory compliance with specific objectives will improve the “software safety goodness”, and thereby reduce the likelihood of software safety failures. For the remainder of this presentation, we will use “belief” in lieu of “confidence” to avoid confusion with probability terminology.

Fuzzy Logic Approach to Risk Estimation (FLARE) DRAFT

- The set of hazard analysis and software development objectives prescribed by a given SwCI linguistic category (*e.g.* A, B, C, or High, Medium, Low) presently produce necessary and sufficient evidence to prove to the safety personnel that the software safety assurance meets the SwCI safety goals for the category
- The software safety analyst is responsible for assessing the veracity of the evidence submitted as proof
- Uncertainties in the assessment process may be due to: (1) human factors, and (2) inadequate data
- These sources of uncertainty are not addressed in the FLARE process
- Instead, FLARE, focuses on standardizing the aggregation of the assessment results from individual evidence items and analyses

Fuzzy Logic Approach to Risk Estimation (FLARE) DRAFT

- The analyst's "belief" in software safety assurance is assumed to be a qualitative estimate of the likelihood for a safe response to software errors.

- FLARE does not specify how the safety analyst must reach their assessment only that they can and do make such an assessment.

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Using FLARE

- FLARE is based on the following assumptions:

(1) As each objective is completed, with sufficient quality, software safety assurance is increased/decreased, which directly correlates to an increased belief in a safe/unsafe response to software errors

(2) Completion of all the prescribed objectives, with sufficient quality, will represent all due diligence required to result in the desired software safety assurance

(3) The qualitative estimate for likelihood of software safety failures depends on the specific objectives completed, the quality of the evidence, and the objective's contribution to software safety assurance.

Using FLARE

- The FLARE process has three high level steps (see Figure 3):

(1) Scoring objectives: Each compliance evidence artifact is assessed against the objective's requirements. Three assessment scoring criteria are used for each artifact: (a) Completeness, (b) Quality, and (c) Contribution. Completeness is an assessment of the percentage of key information provided by each of the evidence artifacts. Quality is an assessment of the goodness of each artifact. The Contribution criteria is an assessment of what extent the objective contributes to changing the likelihood of software safety failures.

(2) **Processing Scores**: The scores for each objective are numeric based inputs. These inputs are processed through a fuzzy logic transformation system to result in a range of possible values for the likelihood - Likelihood Range (P).

(3) **Estimating Risk Possibility**: The Likelihood Range is paired with the hazard severity category to estimate the Software Risk Possibility (SRP) (*e.g.* High, Medium, or Low).

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Using FLARE

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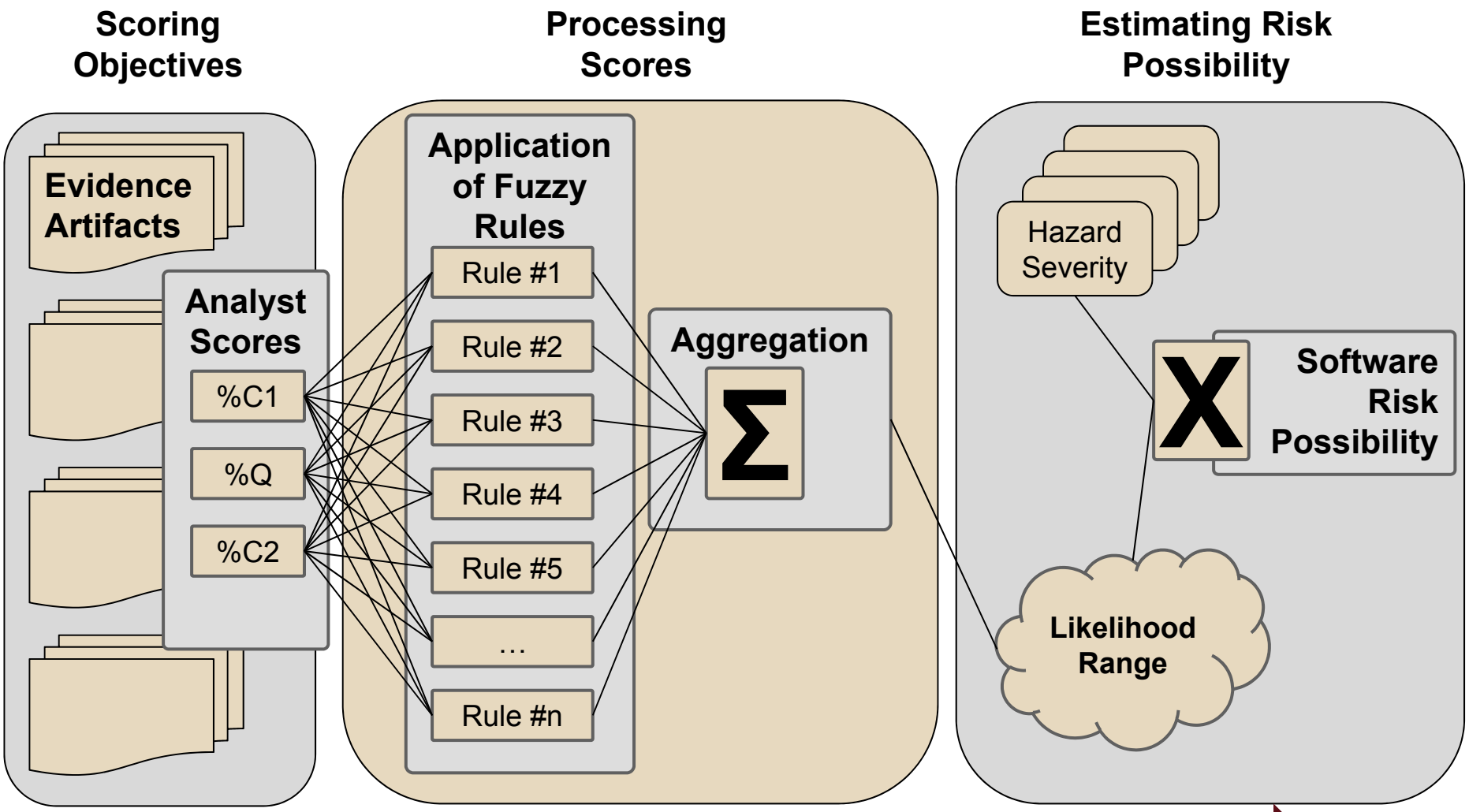

Information flows from left to right.

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Using FLARE

- This section illustrates the FLARE method using the following information set:
  - Hazard Description:
    - Source: Failure condition that prevents continued safe flight and landing, or results in loss of aircraft.
    - Mechanism: Undetected incorrect flight information.
    - Outcome: Death or permanent total disability; system loss
  - Software Contribution: Yes
  - Severity Category: Catastrophic
  - Software Control Category: Autonomous
  - Software Hazard Criticality Index: High (1[I])
  - Level-Of-Rigor (LOR): High (or SwCI-A) (requires significant analysis and testing resources)

Using FLARE

- The Program Manager Handbook for Flight Software Airworthiness provides objectives that must be fulfilled.
- Our example data would require all 108 possible objectives be accomplished to ensure SwCI-A compliance.
- In this context, compliance means complete and high quality evidence/artifacts that establish levels of belief that software error leading to software safety failures have been eliminated or acceptably mitigated.
- The FLARE process is used to evaluate each objective independently.
- For brevity, only one objective is further examined here.

Using FLARE Scoring Objectives

- For the first step in the fuzzy process, the analyst must score each software safety assurance objective by assessing the percent Complete, the percent Quality, and the percent Contribution to software safety assurance.
- The assessment could be in linguistic terms (*e.g.* bad, okay, great) or exact values or interval based values (*e.g.* between 20 and 30%). All of these expressions of assessment can be represented as fuzzy numbers. The FLARE process example illustrates with exact values.
- Each software safety assurance objective plays an independent role of varying degree in the software safety assessment process.
- Fuzzy Logic requires a numerical input that allows a continuous progression from “worst” to “best”.
- The approach chosen to rating Completeness, Quality, and Contribution is to apply percentages ranging from 0% to 100%.

Using FLARE Scoring Objectives

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Example of scoring objectives

Function of SwCI level

List of Objectives	SwCI Level	Complete (%)	Quality (%)	Contribution (%)
Objective 1	A	25	50	96
Objective 2	A	43	87	75
Objective 3	A	89	12	15
. . . .	. . . .	. . . .	. . . .	. . . .
Objective n	A	77	95	45

Determined by the SCHI for a given SCSF (or hazard)

Software Safety Analyst's scores based on review of compliance evidence

Using FLARE Scoring Objectives

Compliance Consideration	Scoring Guidance	Scoring Range
General	Scoring results in a percent compliance value for a given compliance consideration where 0% is “worst” and 100% is “best”.	N/A
Completeness (C)	Consider what key information is required to completely meet the requirements, or fully satisfy the objective. What percentage of the key information is addressed in the evidence? No key information would result in a score of 0% while all key information would result in a score of 100%.	0% <= C <= 100%
Quality (Q)	Consider the goodness, or grade, of the key information provided in the evidence. Do not consider the quality of key information not provided. Only consider the key information actually provided as evidence. Extremely low quality results in a score of 0% while extremely high quality results in a score of 100%.	0% <= Q <= 100%
Contribution (P)	Assume the evidence provided is 100% complete and 100% quality. To what extent does the SwCI objective directly impact software safety assurance? No impact would result in a score of 0% while a very large impact would result in a score of 100%.	0% <= P <= 100%

Using FLARE Scoring Objectives

- Scoring Example
- For the remaining steps in the FLARE description, the example test case only considers a single assurance objective, “FHA is developed”.
- The associated scores are: Completeness = 64%, Quality = 28%, and Contribution = 84%.

A Few Actual Objectives	SwCI Level	Complete (%)	Quality (%)	Contribution (%)
Integrated master schedule for the system/software development is established	A	25	50	15
FHA is developed	A	64	28	84
System safety requirements are traceable to the FHA	A	30	45	95

Using FLARE Processing Scores

•Fuzzy sets and fuzzy numbers are used to represent “possible” values either as discrete items in a set or as continuous numeric values.

•The idea of what is “possible” is important to FLARE since there is some research that suggests that analysts assess possibilities in problems with uncertainty.

• Given that FLARE uses analyst assessments, representing and manipulating “possibility” seems natural.

•Fuzzy logic provides methods for performing logical operations on these fuzzy values and a fuzzy calculus can provide methods for performing math operations on fuzzy numbers.

•

•Each fuzzy set can be identified by a linguistic variable scale to facilitate human interaction.

•Odd numbers of values in the scales are used to permit a middle ground to be stated.

Using FLARE Processing Scores

- FLARE utilizes linguistic values to characterize five key variables with five possible values in each scale: three are input variables, one is an intermediate variable, and one is an output variable.
- The input variables are Completeness (X), Quality (Y), and Contribution (Z).
- The intermediate variable is Belief (T) and the output variable is Likelihood Range (P).
- Each linguistic variable can have a defined set of values such as are described below:
  - Completeness = [*Mostly Incomplete, Some Information, Some Key Information, Most Key Information, All Key Information*]
  - Quality = [*Inferior, Below Average, Average, Above Average, Superior*]
  - Contribution = [*Very Small, Small, Moderate, Large, Very Large*]
  - Belief = [*Very Low, Low, Medium, High, Very High*]
  - Likelihood Range = [*Frequent, Probable, Occasional, Remote, Improbable*]

Using FLARE Processing Scores

- Using human analyst oriented value ranges described using words like those above or words like “Small” and “Very Small” gives a relative association without defining hard boundaries.

- However, in order to make these relative associations meaningful, they must be associated with numeric sub-ranges of possible values that match reasonable responses from the linguistic population, *i.e.* the analysts.

- Representation of these responses is accomplished through the development of a range of possible numeric values for each linguistic value.

- In fuzzy logic, this range of possible values is represented by the “**membership function**”.

- Thus the “**membership function**” relates the members of a given linguistic value on a numeric value scale.

Using FLARE Processing Scores

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- In the case of the input variables, Completeness, Quality, & Contribution, the fuzzy value sub-ranges are taken from the full range of possible compliance scores (*i.e.* 0% to 100%).
- An example membership function for Completeness = "*Some Key Information*" is shown below.
- Note that the "*Some Key Information*" membership function will only respond to the sub-range of analyst's estimates of Completeness scores ranging from 30% to 70%.
- The shape of this membership function is not a square or rectangle of abrupt change because this function represents a decreasing possibility of membership in "Some Key Information" as the values move away from 50%.

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Using FLARE Processing Scores

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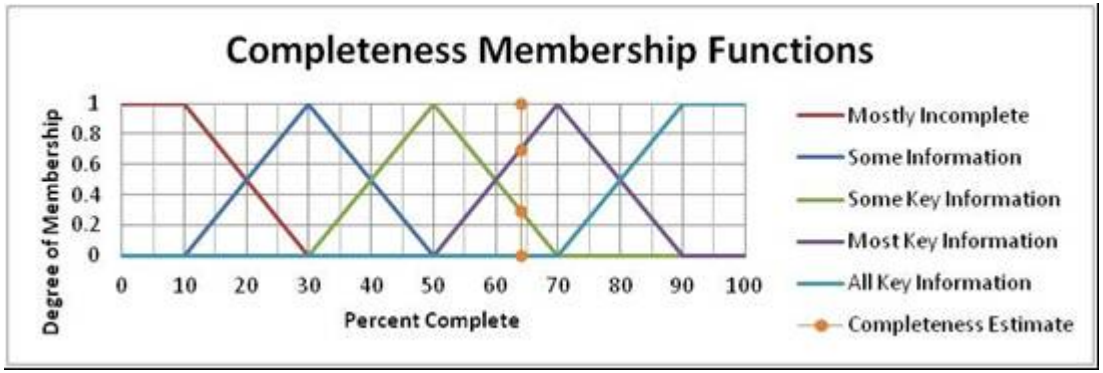

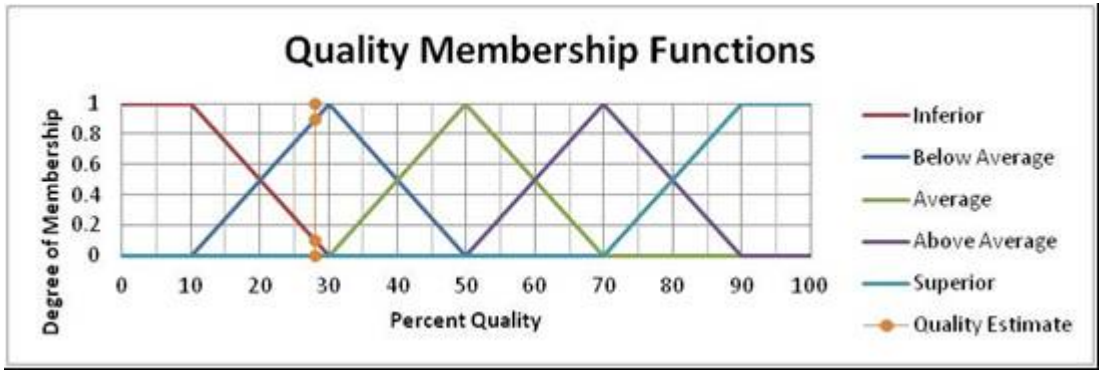

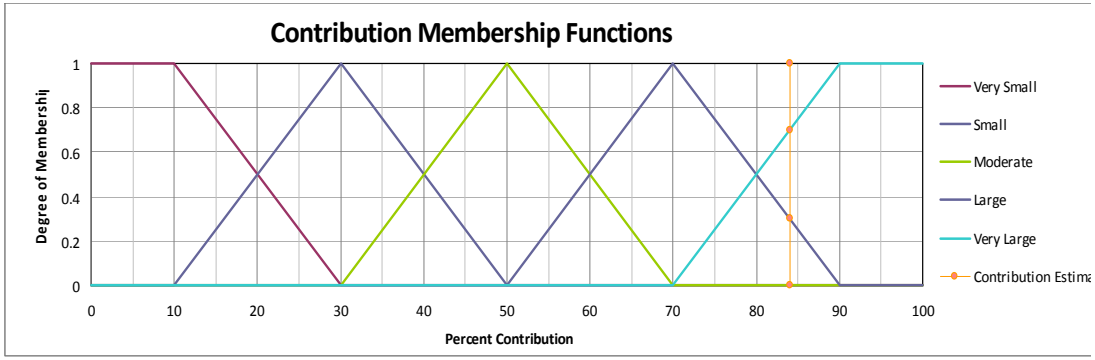

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Using FLARE Processing Scores

Linguistic Variable	Analyst Score Value	Linguistic Set Values	Degree-of-Membership
Completeness	64%	Some Key Information	0.3
	64%	Most Key Information	0.7
Quality	28%	Inferior	0.1
	28%	Below Average	0.9
Contribution	84%	Large	0.3
	84%	Very Large	0.7

Using FLARE Processing Scores

- Examine the Completeness variable.
- Note that the Completeness variable has a degree of membership of 0.3 that completeness is described by the linguistic value “Some Key Information”.
- It also has a degree of membership of 0.7 that Completeness is described by “Most Key Information”.
- FLARE must account for both possible values.
- FLARE uses a fuzzy “rule” approach vice a fuzzy numeric approach to accomplish this.
- The “rules” describe relationships between values and linguistic variables.

Using FLARE Processing Scores

- Fuzzy logic systems use “rules” to describe relationships between the linguistic variables that comprise the FL system (FLS).
- In a sense the rules are the logic component of the FLS.
- Two rules are used in our fuzzy system. Their general expression in linguistic “if-then” format is shown below:
  - If Completeness = X and Quality = Y then Belief = T (Expression 1)
  - If Perfection = Z and Belief = T then Likelihood Range = P (Expression 2)
- We have created two rule matrices to define the fuzzy rule responses.
- The rule matrices will be employed later in the fuzzy process to estimate our Belief (T) in the compliance evidence and the Likelihood Range (P).

Using FLARE Processing Scores

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- The Belief rule matrix is a mapping of the Completeness and Quality values to a Belief value.
- The Likelihood Range rule matrix maps the Belief and Contribution values to the Likelihood Range values

Belief (T)		Completeness (X)				
		Mostly Incomplete	Some Information	Some Key Information	Most key Information	All Key Information
Quality (Y)	Inferior	VL	VL	VL	VL	VL
	Below Average	VL	L	L	L	L
	Average	VL	L	M	M	M
	Above Average	VL	L	M	H	H
	Superior	VL	L	M	H	VH

Very Low (VL) Low (L) Medium (M) High (H) Very High (VH)

Likelihood Range (P)		Belief (T)				
		Very Low	Low	Medium	High	Very High
Contribution (Z)	Very Small	O	R	R	R	I
	Small	O	O	R	R	I
	Moderate	P	O	O	R	I
	Large	P	P	O	R	I
	Very Large	F	P	O	R	I

Frequent (F), Probable (P), Occasional (O), Remote (R), Improbable (I)

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Using FLARE Processing Scores

- Using the associations from the Belief rule matrix the following rules are derived for the example data. Values in parentheses are specific degree-of-membership values.
  - **If** Completeness = *Some Key Information* (0.3) **and** Quality = *Inferior* (0.1) **then** Belief = *Very Low* (0.1)
  - **If** Completeness = *Most Key Information* (0.7) **and** Quality = *Inferior* (0.1) **then** Belief = *Very Low* (0.1)
  - **If** Completeness = *Some Key Information* (0.3) **and** Quality = *Below Average* (0.9) **then** Belief = *Low* (0.3)
  - **If** Completeness = *Most Key Information* (0.7) **and** Quality = *Below Average* (0.9) **then** Belief = *Low* (0.7)

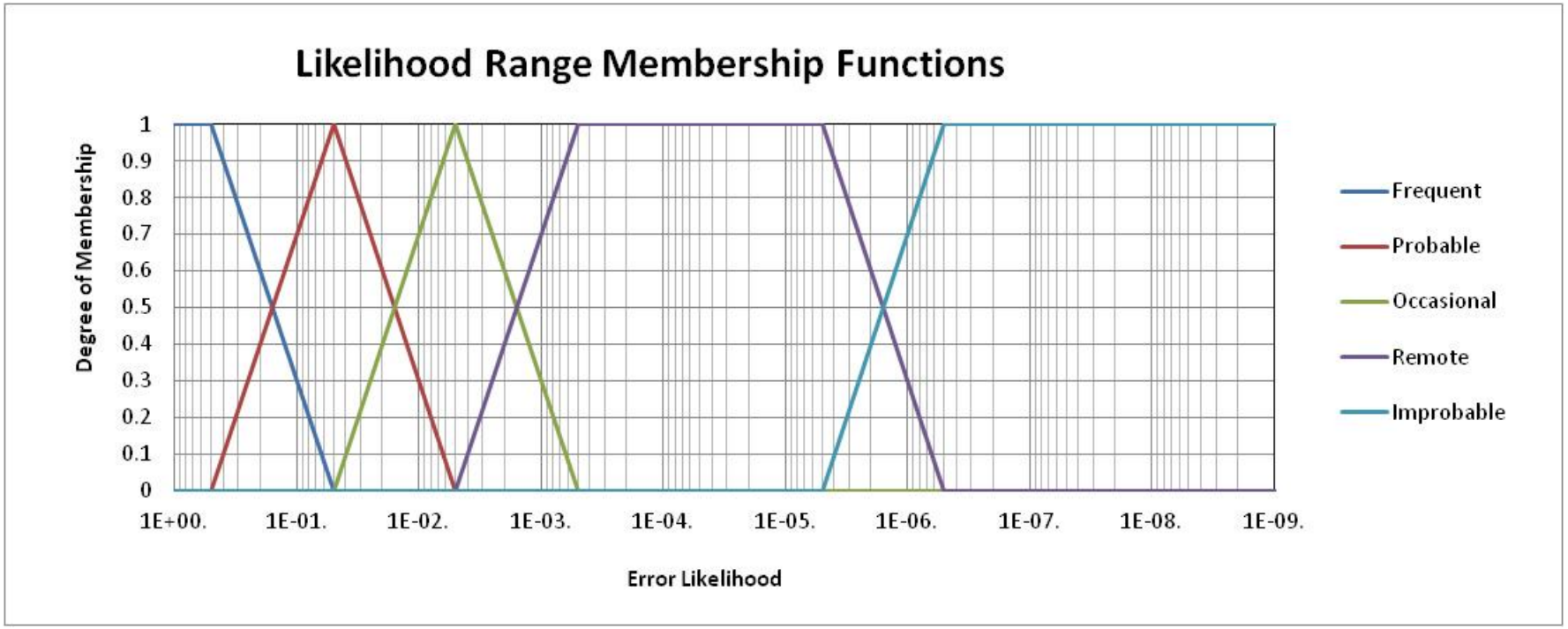
NOTE
The fuzzy "AND" operation results in the smallest of the antecedent membership degrees being assigned to the confidence membership function.

Using FLARE Processing Scores

- The Likelihood Range rules are shown below:
  - **If** Belief = *Very Low* (0.1) **and** Contribution = *Large* (0.3) **then** Likelihood Range = *Probable* (0.1)
  - **If** Belief = *Very Low* (0.1) **and** Contribution = *Very Large* (0.7) **then** Likelihood Range = *Frequent* (0.1)
  - **If** Belief = *Low* (0.3) **and** Contribution = *Large* (0.3) **then** Likelihood Range = *Probable* (0.3)
  - **If** Belief = *Low* (0.3) **and** Contribution = *Very Large* (0.7) **then** Likelihood Range = *Probable* (0.1)
  - **If** Belief = *Low* (0.7) **and** Contribution = *Large* (0.3) **then** Likelihood Range = *Probable* (0.3)
  - **If** Belief = *Low* (0.7) **and** Contribution = *Very Large* (0.7) **then** Likelihood Range = *Probable* (0.7)

Using FLARE Processing Scores

- Figure below shows the membership functions for Likelihood Range.
- Note that this is a decreasing value size logarithmic scale on the positive X-axis.
- The sub-ranges for the membership functions are derived from MIL-STD-882E



Using FLARE Processing Scores

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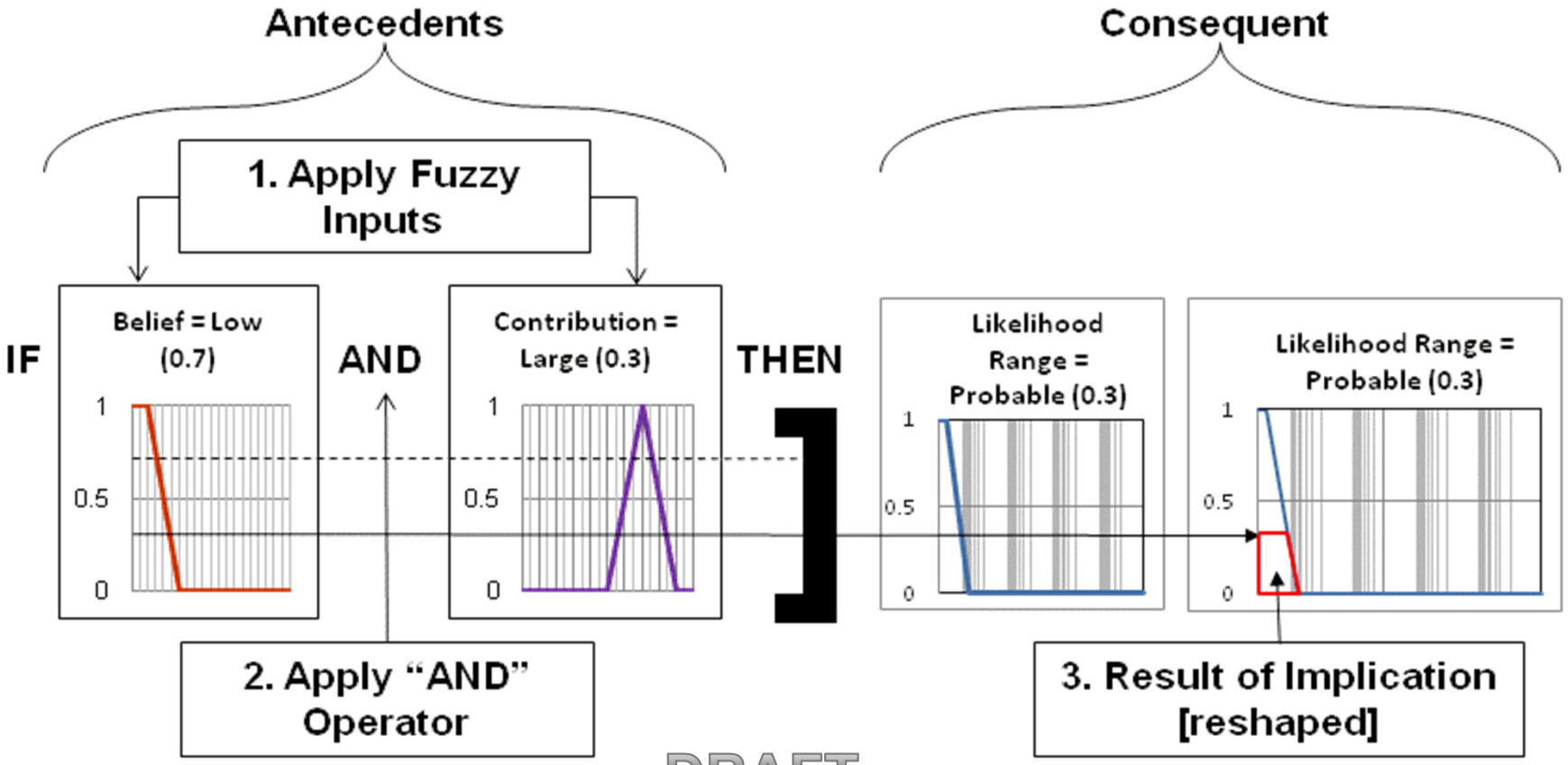
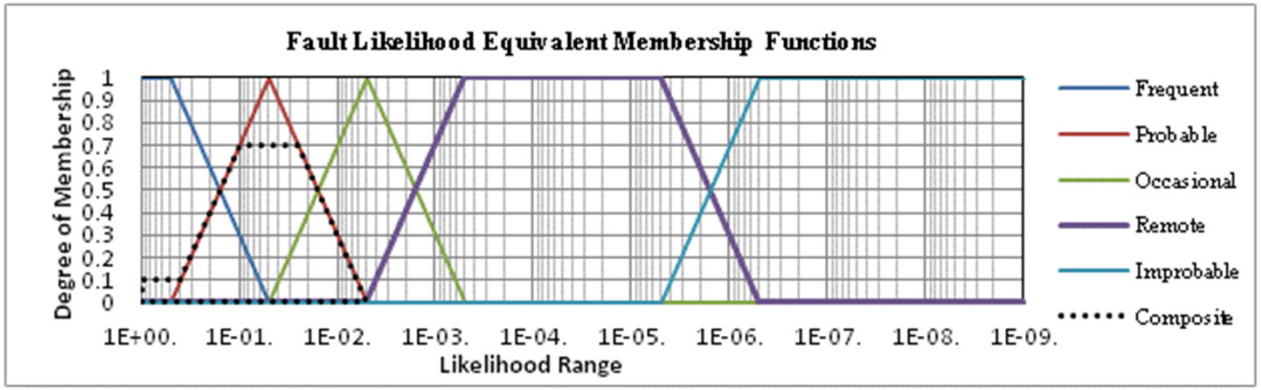
- From the Likelihood Range membership functions, a composite membership polygon is created.
- The individual modified membership functions create membership polygons which are combined to form a composite membership polygon.



Using FLARE Processing Scores

- From the individual Likelihood Range membership functions we create a composite membership polygon using the modified boundaries of the individual membership functions.
- The highest membership of the Frequent membership function is 0.1 and for the Probable function is 0.7. No other functions were intersected.
- The individual modified membership functions create membership polygons which are combined to form a composite membership polygon.
- The composite membership polygon is the dotted black line.



Using FLARE Processing Scores

- The FLARE process uses a conservative approach and chooses the Likelihood Range value with the highest degree-of-membership, *i.e.* the most possible, to estimate the likelihood for software safety failure.
- If the degrees-of-membership are equal, FLARE chooses the left-most membership function (highest likelihood) on the graph.
- The result for the example data is Likelihood Range = “Probable”

Example Objective	SwCI	Completeness (X) (%)	Quality (Y) (%)	Contribution (Z) (%)	Likelihood Range (P)
FHA is developed	A	64	28	84	Probable

Using FLARE
Estimating Risk Possibility

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- In order to express this likelihood in terms of qualitative risk the likelihood must be paired with the SwCI severity.
- The FLARE team is currently examining approaches for this calculation. This section discusses one approach currently being evaluated.
- Using Likelihood Range value “Probable” and the Severity Category of “Catastrophic” from the example data the Software Risk Possibility (SRP) is 1B.
- The color coding in the SRP table corresponds to risk acceptance levels High (red), Serious (orange), Medium (yellow), and Low (green)..

Software Risk Possibility (SRP)		Likelihood Range (P)				
		Frequent (A)	Probable (B)	Occasional (C)	Remote (D)	Improbable (E)
SHCI Severity	Catastrophic (1)	1A	1B	1C	1D	1E
	Critical (2)	2A	2B	2C	2D	2E
	Marginal (3)	3A	3B	3C	3D	3E
	Negligible (4)	4A	4B	4C	4D	4E

Using FLARE Estimating Risk Possibility

- Using the FLARE process allows the compliance evidence for each assurance objective to be assessed independently from all other objectives.
- This in turn allows the analyst to portray the specific objectives which need the most attention.
- For example, if all the objectives for the example hazard information are assessed the results would provide the SRP value and qualitative risk for each objective.
- The qualitative software risk information can be portrayed with intrinsic resource allocation priorities for risk reduction activities.

Using FLARE Estimating Risk Possibility

- In the table below, we assume two out of the 108 objectives contribute "Frequent" likelihood of software safety failures and 106 objectives contribute "Improbable" likelihood.
- Since "Catastrophic" severity and "Frequent" likelihood indicate the overall risk is "High", the program office (PO) will need to reduce the "Frequent" likelihood for two specific objectives to the "Improbable" range in order to accept the residual risk without higher command approval.
- With this method, the PO can target unique risk reduction actions to specific assurance objectives based on the analysis details.

Software Risk Category (SRC)		Likelihood Range (P)				
		Frequent (A)	Probable (B)	Occasional (C)	Remote (D)	Improbable (E)
SHCI Severity	Catastrophic (1)	2	0	0	0	106
	Critical (2)	0	0	0	0	0
	Marginal (3)	0	0	0	0	0
	Negligible (4)	0	0	0	0	0

Using FLARE
Estimating Risk Possibility

- All the Likelihood Range values in the example need to be “Improbable” at the least in order to lower the overall qualitative SRP to Medium (yellow colored blocks).
- The tables below show the risk gaps in terms of percent Complete and percent Quality.

Example Objective	SwCI Level	Complete (%)	Quality (%)	Contribution (%)	Likelihood Range	SRP	Qualitative Risk
FHA is developed	A	64	28	84	Probable	1B	High

Example Objective	SwCI Level	Complete (%)	Quality (%)	Contribution (%)	Likelihood Range	SRP	Qualitative Risk
FHA is developed	A	Increase score from 64 to 81	Increase score from 28 to 81	84	Improbable	1E	Medium

Using FLARE
Estimating Risk Possibility

- The Completeness and Quality gaps are now known in terms of percent.
- This knowledge must be transitioned into actions that close or minimize the compliance gaps.
- Since the analyst has already reviewed the compliance evidence it is assumed the analyst kept a log of the review.
- The log may look similar to the table below.
- From the information contained in the review log the analyst can very specifically identify recommendations to assist the developer in providing the necessary compliance evidence that would lead to achieving the desired risk possibility.

#	Date	Page	Section	Paragraph	Comment Text (Provide clear succinct comments)	Recommendation (Must provide recommended rewording or appropriate solution)	Rationale	Comment Initiator

FLARE Summary

- The FLARE process incorporates and uniquely handles four difficult issues that plague software system safety hazard analyses:
  - Estimating software failure probability is very difficult and expensive,
  - Decisions are subjective,
  - Data are imprecise, and
  - Software safety risk is never quantified or qualified.

- Two key advantages of FLARE are:
  - Specific (highly focused) risk reduction activities can be recommended to the PO and/or developer
  - Qualitative software risk possibility can be compared on par with hardware and operations risk estimates.

- Almost every step in the FLARE process can be tailored to a program's unique requirements
- The FLARE process is easily automated.

FLARE
Future Direction

- During the development of the basic FLARE process, the team encountered several items that require additional examination.
- Among the high interest items are the analyst's belief in the rules stated previously. This is distinct from the belief in the data sets and it requires additional steps to account for this factor. These steps are not addressed above.
- A second high interest item is utilization of a fuzzy mathematical approach as an alternative to the rule based approach shown here.
- Develop consistent criteria for assessing percent Complete and percent Quality.
- Develop standardized values for percent Contribution using SME input.
- Assess whether the Likelihood Range membership with the highest membership degree should represent the Likelihood Range or should the priority be area of the membership polygon?