Traceability Beyond Source Code: An Elusive Target?

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Outline

- Introduction
- Overview
- Examples from industrial research projects
- Reflections and conclusions

Traceability

- The ability to follow the life of software artifacts, in both a backward and forward direction, e.g., requirements, design decisions, test cases.
- Requirements traceability: Trace a requirement from its emergence to its fulfillment.
- Motivations:
  - Understand rationale
  - Assess impact of change
  - Certification, auditing, compliance with standards

Motivations

- Traceability research is source-code-centric
- Certification (safety, privacy …)
- Change management: Impact analysis, design rationale, regression testing …
- Change management is a key challenge to certification
- Traceability analysis is a system-level activity

Challenges

- Establishing and maintaining traces is typically expensive
- Automation, in most cases, does not provide the level of accuracy required
- The benefits of exploiting traces are still unclear in many contexts
- Highly contextualized: A great deal of variation in development contexts entails a great deal of variation in traceability solutions
- Targeted analysis of traces drives traceability solutions

Requirements

- Hundreds or thousands of them
- Higher-level requirements (usually from customers) decomposed into lower-level ones (analysts)
- Some more critical than others
- Constantly changing and evolving: A stronger argument for the economic benefits of traceability

Modeling

- In many application domains where traceability is required, system and software modeling is a rising practice

- Provisions in standards lead to modeling

- IEC 61508 (meta-standard), DO-178B (Avionics), EN50129 (Railways), ISO 26262 (Automotive)

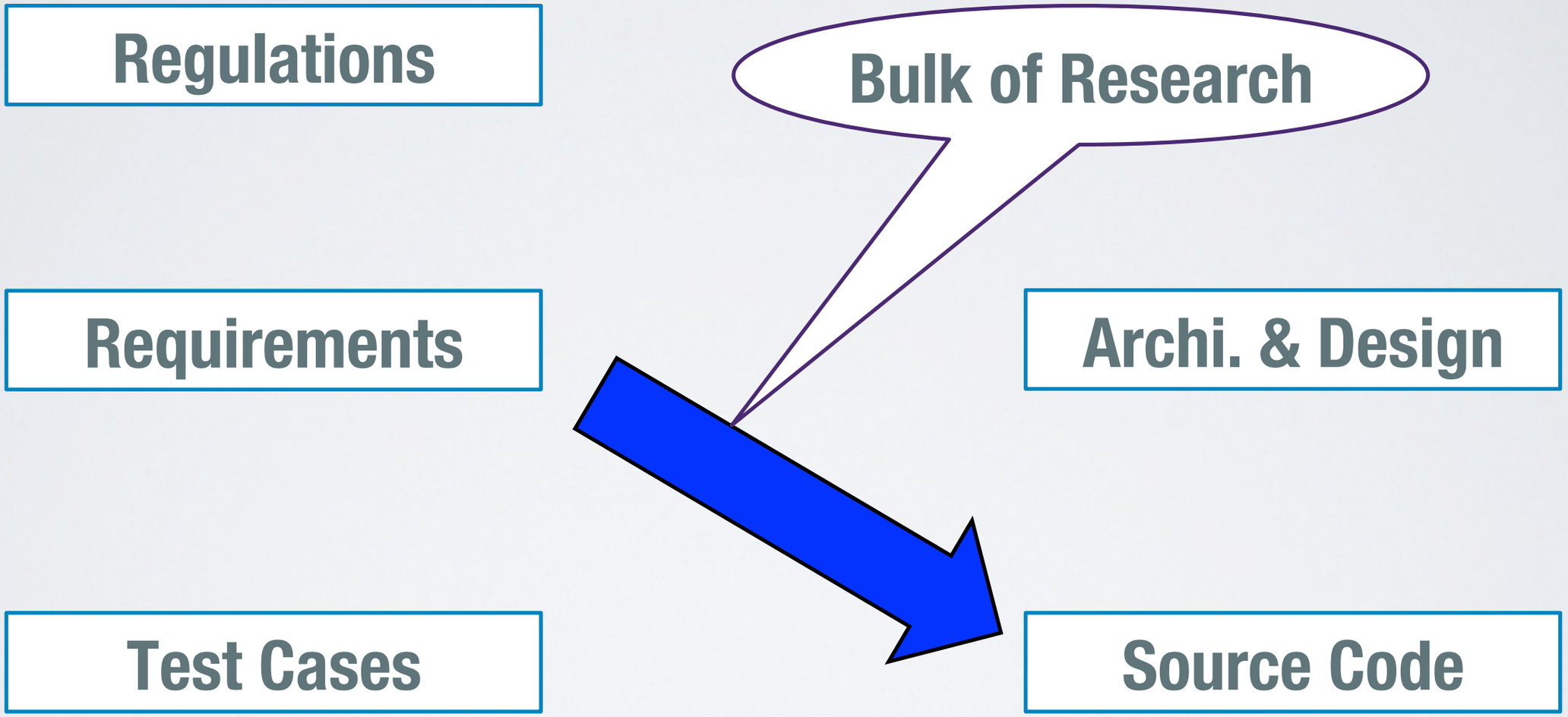
- UML, SysML, Simulink, …

Economic Decision

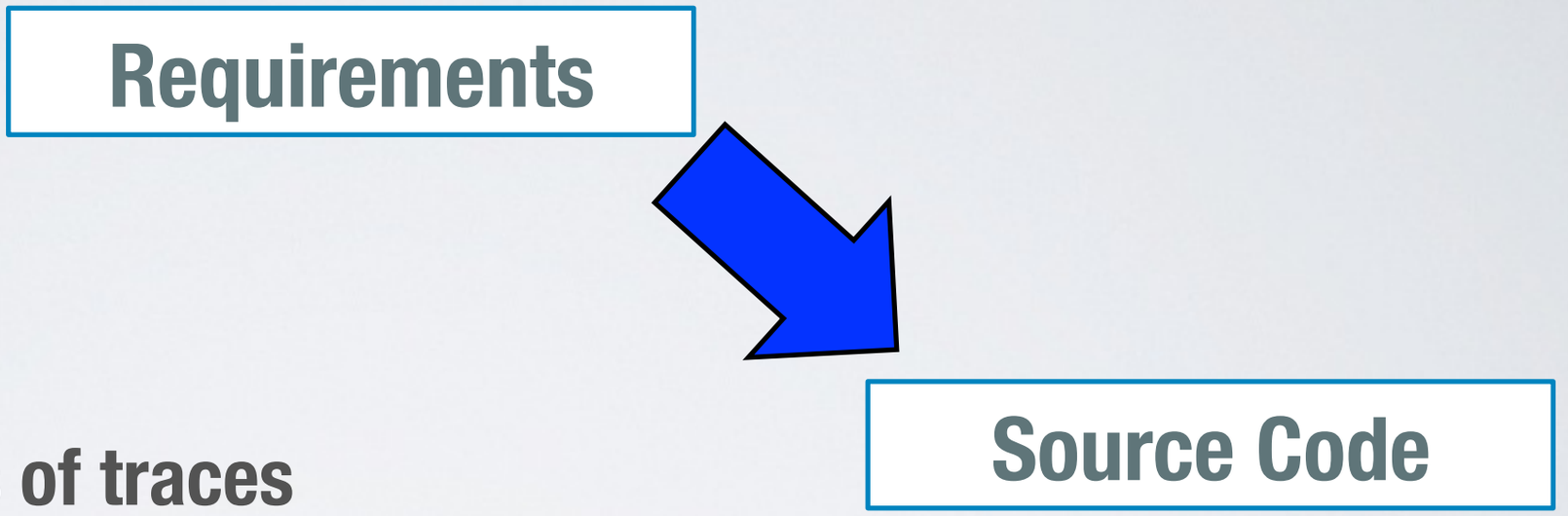
- Not just about trace “accuracy” …
- Economic trade-off
  - Cost: Establishing and maintaining traces
  - Benefit: More accurate decisions, decrease in human effort
- Decision science
- Makes it hard to study, out of context, as it determines effort and benefits

Overview

Traceability at a Glance

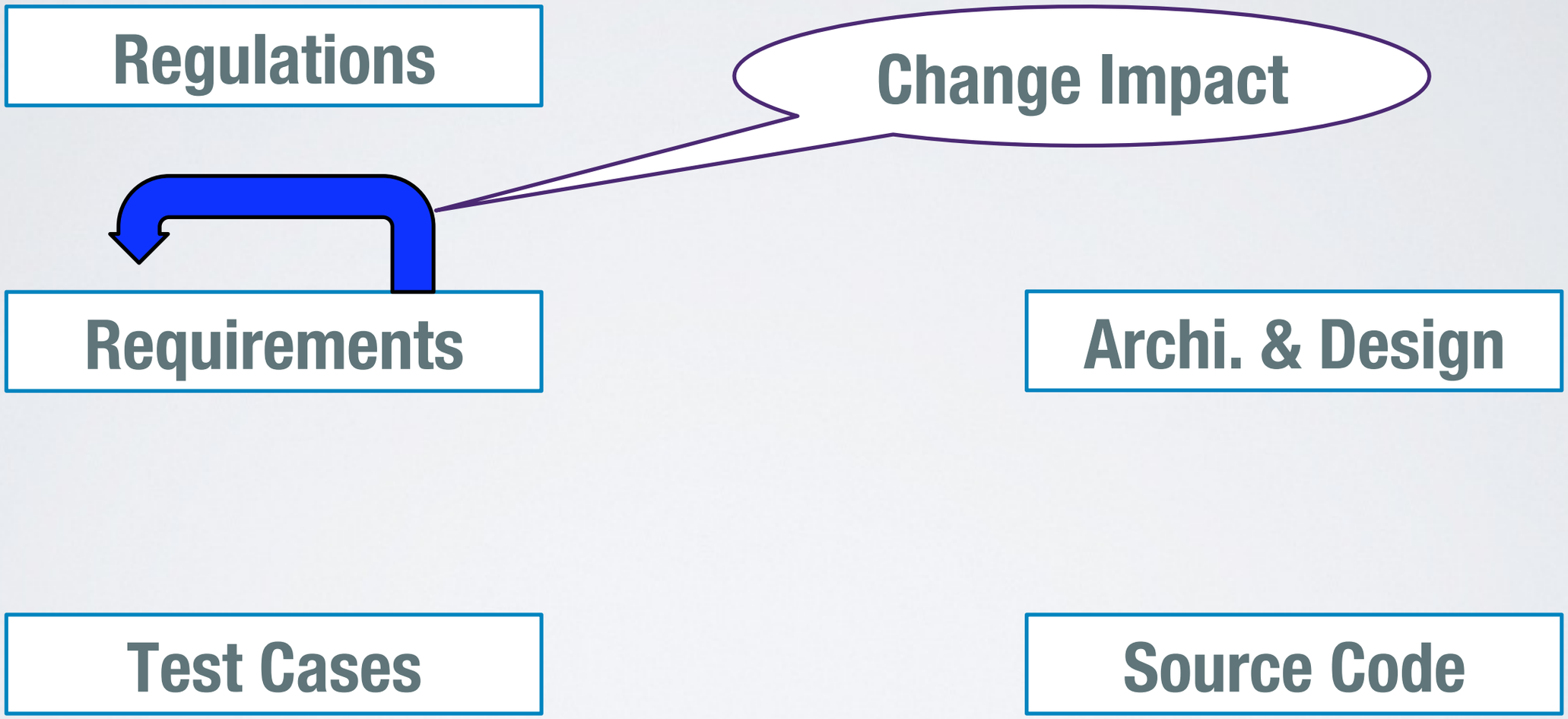


Requirements-Source Code



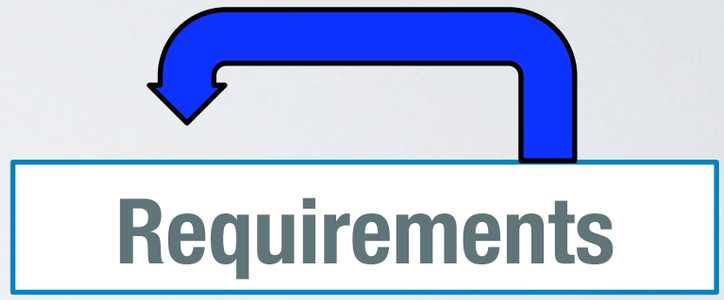
- Natural language
- Hundreds or thousands of traces
- Information Retrieval & Natural Language Processing
- Coding conventions
- Level of granularity?
- Minimum accuracy for ensuring practicality? Few human studies …

Traceability at a Glance



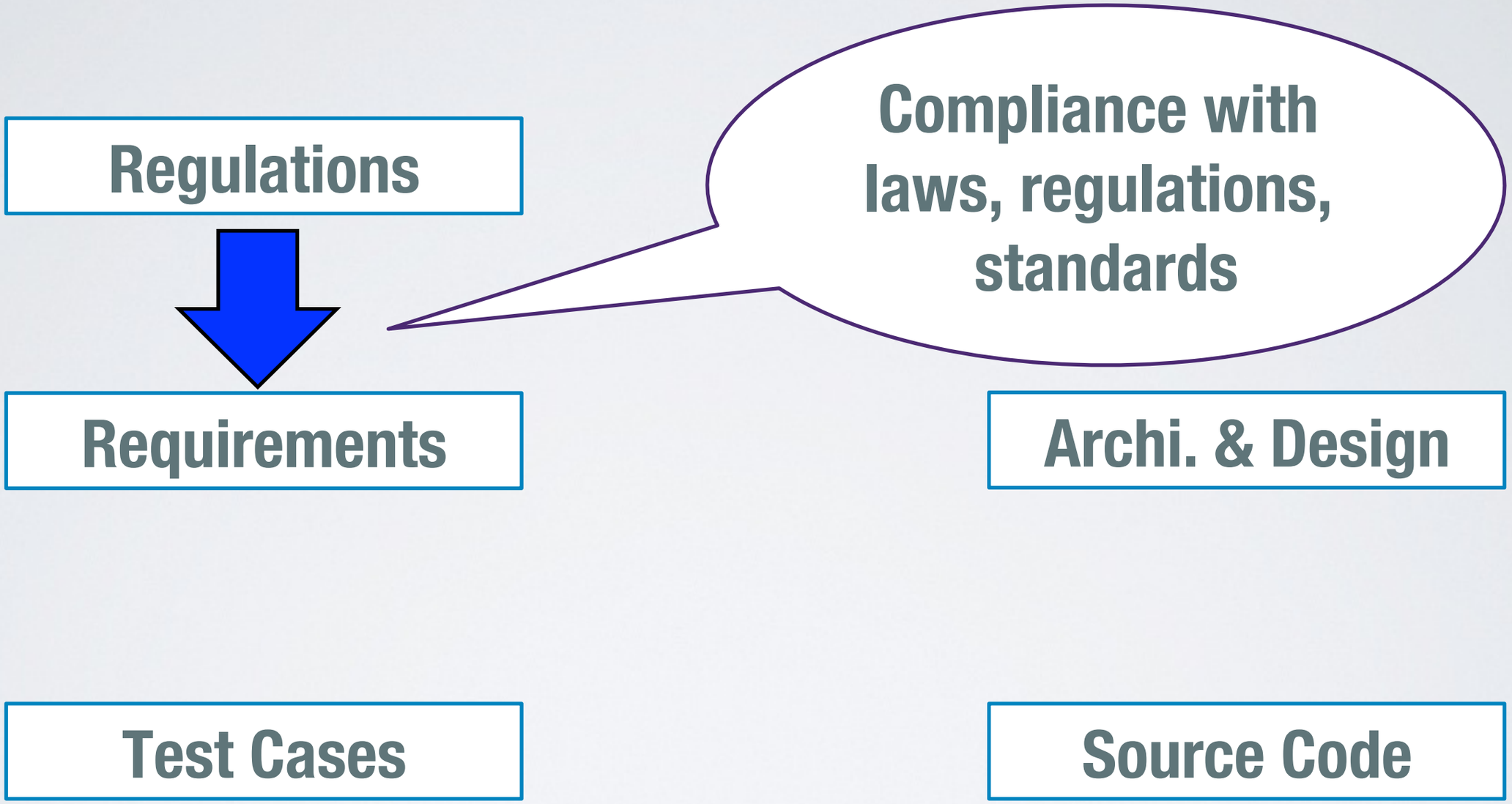
Requirements-Requirements

- Mostly natural language
- Sometimes structured (template)
- Hundreds of traces



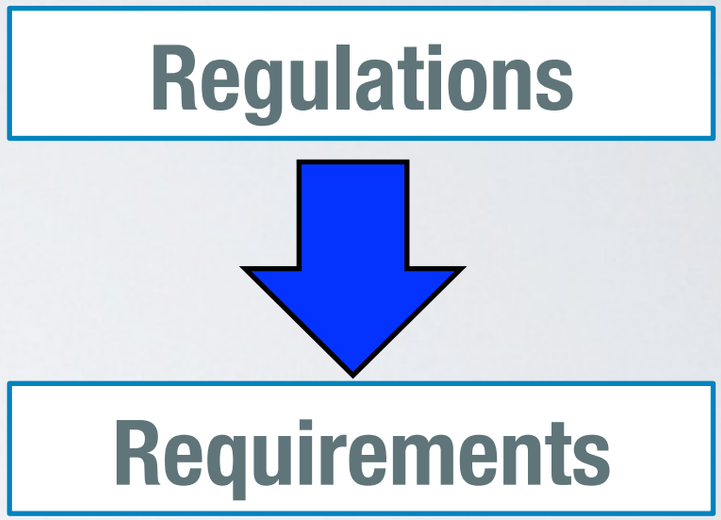
- Domain terminology, concepts, and their relationships are key to discovering traces among requirements
- Syntactic and semantic similarity measures

Traceability at a Glance



Standards-Requirements

- Many standards, laws, and regulations
- They must be interpreted in context
- Compliance must be ensured
- Critical systems: Risks and hazards
- Requirements as mitigations
- Subjectivity, residual risks

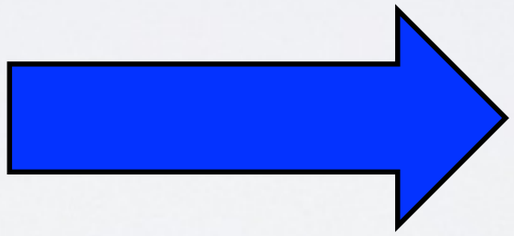


Traceability at a Glance

Regulations

Certification, change management

Requirements



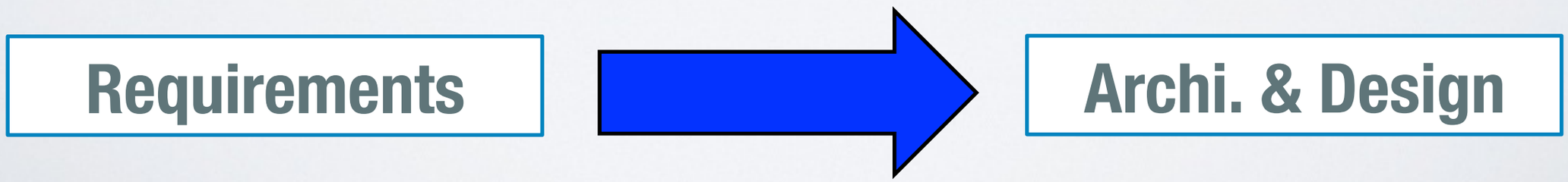
Archi. & Design

Test Cases

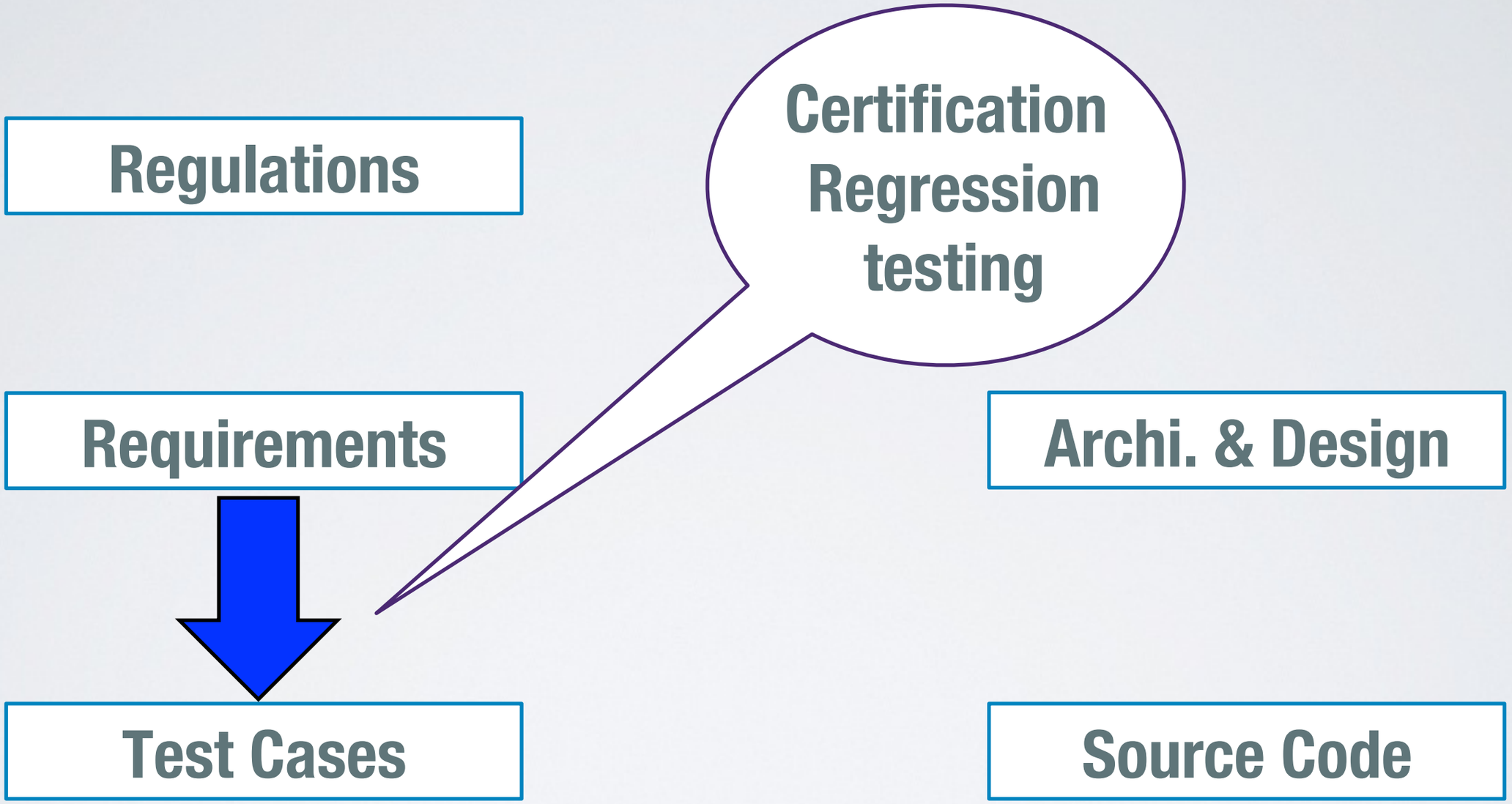
Source Code

Requirements-Design

- Capture the rationale of design decisions
- Support evolution, avoid violating essential design decisions
- Useful for impact analysis based on traces
- What is a rationale? Level of granularity?
- Design representation?

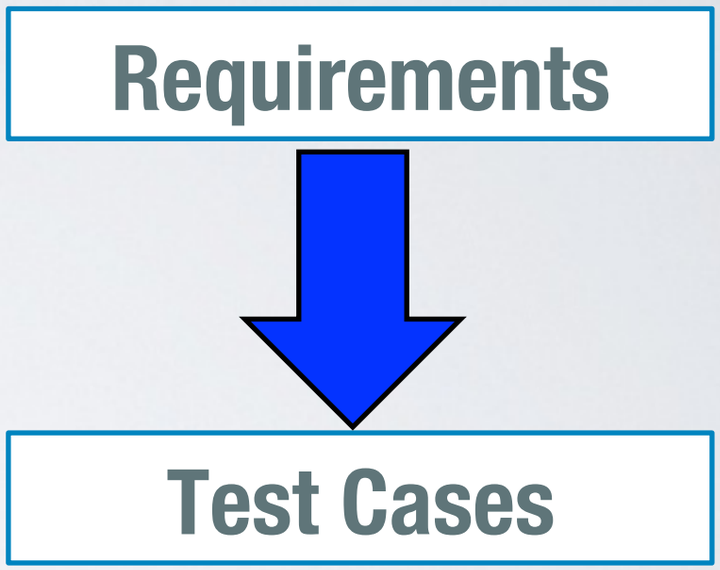


Traceability at a Glance

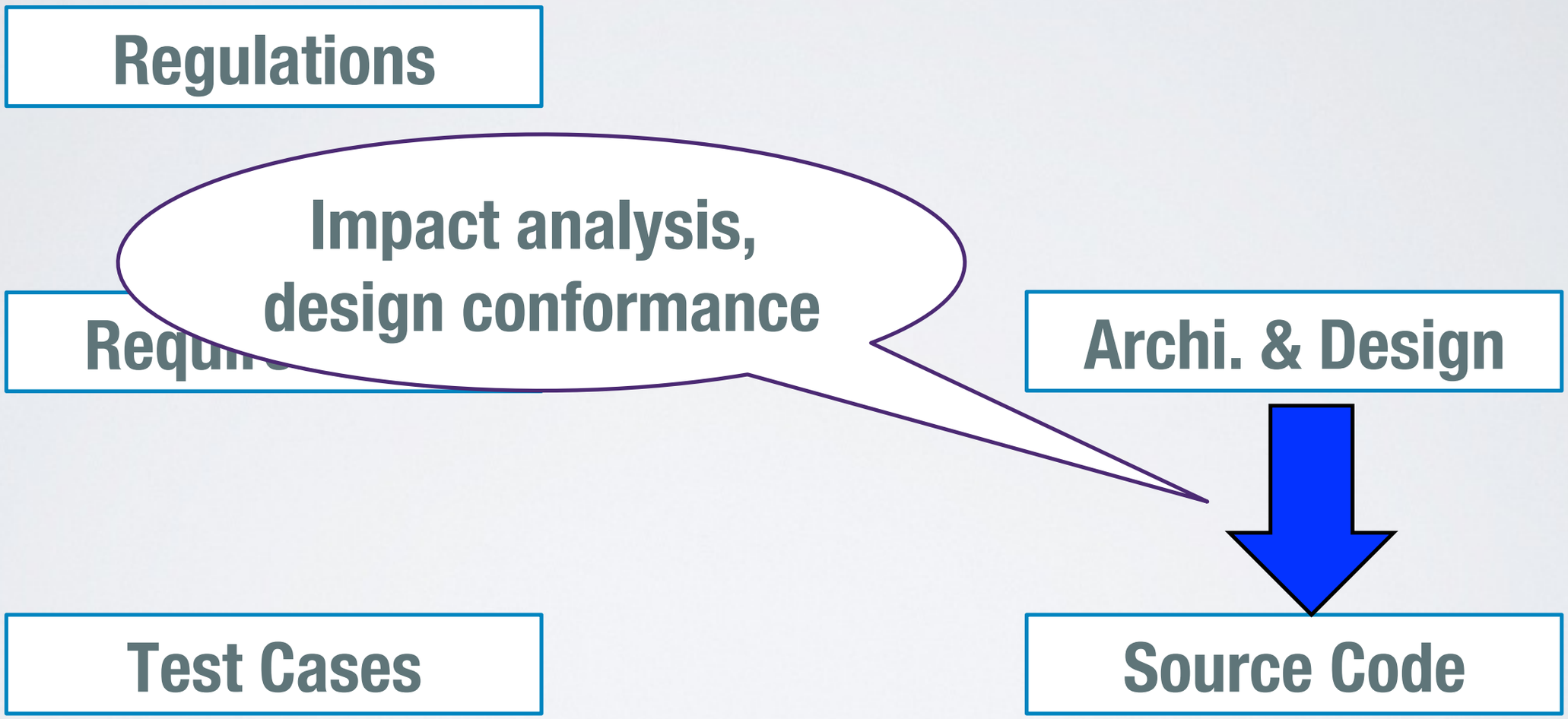


Requirements-Test Cases

- Requirements “coverage” required by standards
- Normally many test cases per requirement
- Thousands of traces
- Regression testing
- Precise impact analysis requires explicit test strategy and rationale
  - How were test cases derived from requirements?
  - Representation of requirements matters



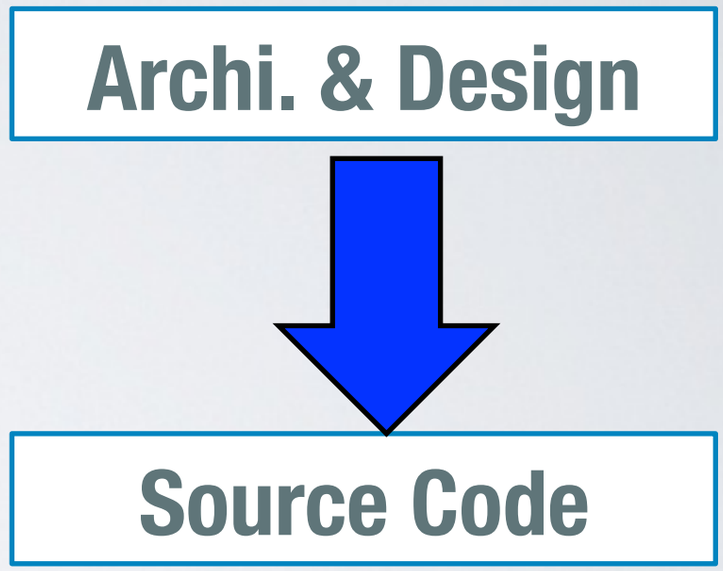
Traceability at a Glance



Design-Source Code

- Ideally, code should be generated from design models, e.g., controllers with Simulink

- This would lead to “free” traceability

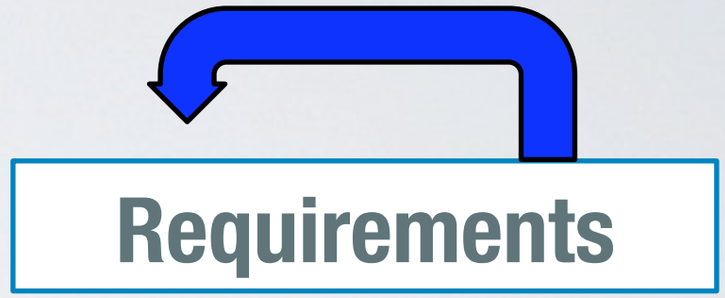


- In practice, not always that simple …

Example Projects

Requirements-Requirements

[RE 2015, TSE 2015, ESEM 2014, ESEM 2013]



SES
your satellite company

Case-A

- 160 Requirements
- 9 change scenarios

novay

Case-B

- 72 Requirements
- 5 change scenarios

Example

- **R1:** The mission operation controller shall transmit satellite status reports to the user help desk.
- **R2:** The satellite management system shall provide users with the ability to transfer maintenance and service plans to the user help desk.
- **R3:** The mission operation controller shall transmit any detected anomalies with the user help desk.

Example

- **R1:** The mission operation controller shall transmit satellite status reports to the user ~~help desk~~ document repository.
- **R2:** The satellite management system shall provide users with the ability to transfer maintenance and service plans to the user help desk.
- **R3:** The mission operation controller shall transmit any detected anomalies with the user help desk.

Challenge#1 - Capture Changes Precisely

- R1: The mission operation controller shall transmit satellite status reports to the user ~~help desk~~ document repository.
- R2: The satellite management system shall provide users with the ability to transfer maintenance and service plans to the user help desk.
- R3: The mission operation controller shall transmit any detected anomalies with the user help desk.

Challenge#2 - Capture Change Rationale

- R1: The mission operation controller shall transmit satellite status reports to the user ~~help desk~~ document repository.
- R2: The satellite management system shall provide users with the ability to transfer maintenance and service plans to the user help desk.
- R3: The mission operation controller shall transmit any detected anomalies with the user help desk.

Challenge#2 - Change Rationale

- R1: The mission operation controller shall transmit satellite status reports to the user ~~help desk~~ document repository.
- R2: The satellite management system shall provide users with the ability to transfer maintenance and service plans to the user help desk.
- R3: The mission operation controller shall transmit any detected anomalies with the user help desk.

Rationales:

R1: We want to globally rename “user help desk”
R2: Avoid communication between “mission operation controller” and “user help desk”
R3: We no longer want to “transmit satellite status reports” to “user help desk” but instead to “user document repository”

Solution Characteristics

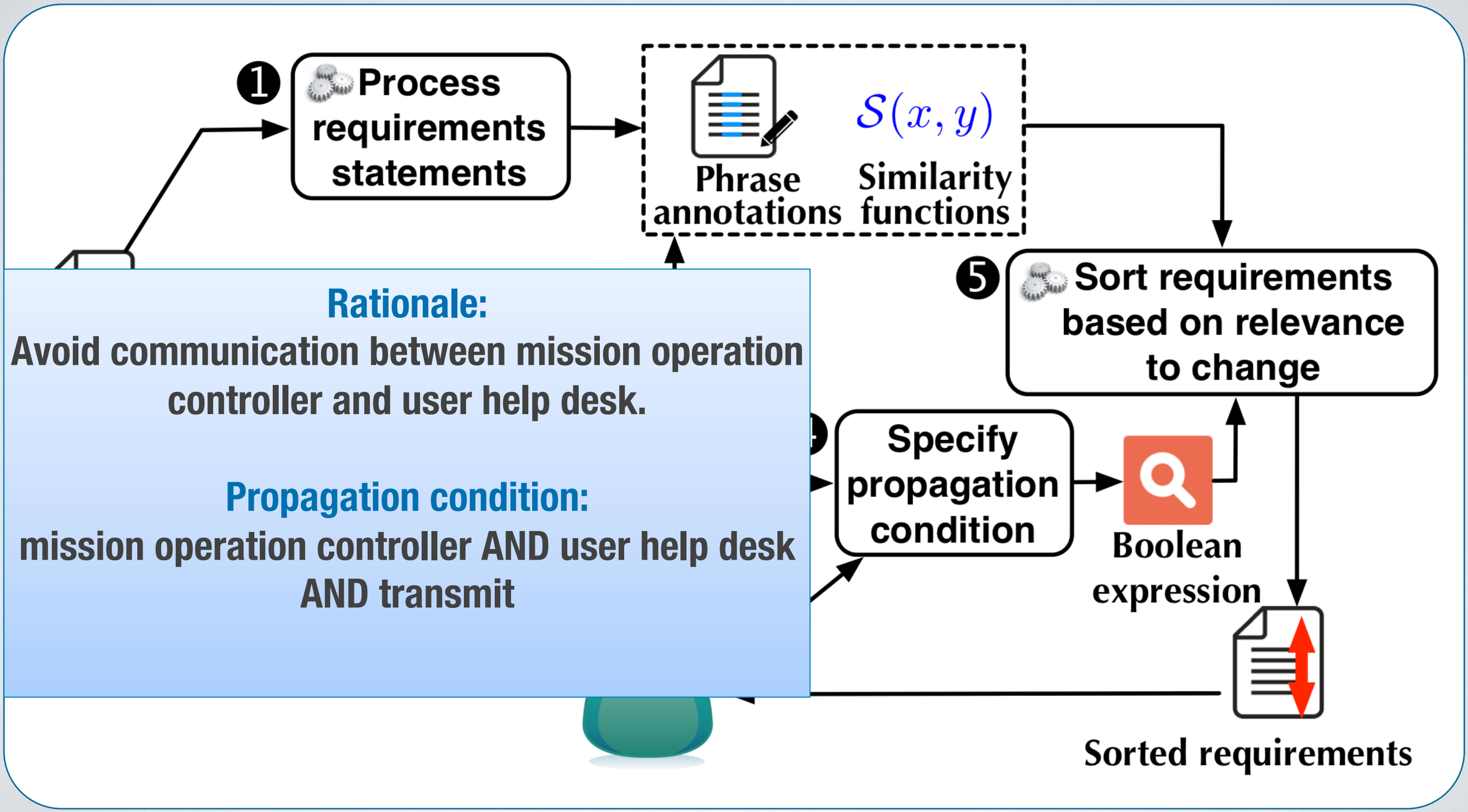
- **Accounts for the phrasal structure of requirements**

  The mission operation controller shall transmit satellite status reports to the user ~~help desk~~ document repository.

  user help desk, Deleted
  user document repository, Added

- **Account for semantically-related phrases that are not exact matches and close syntactic variations**

Approach



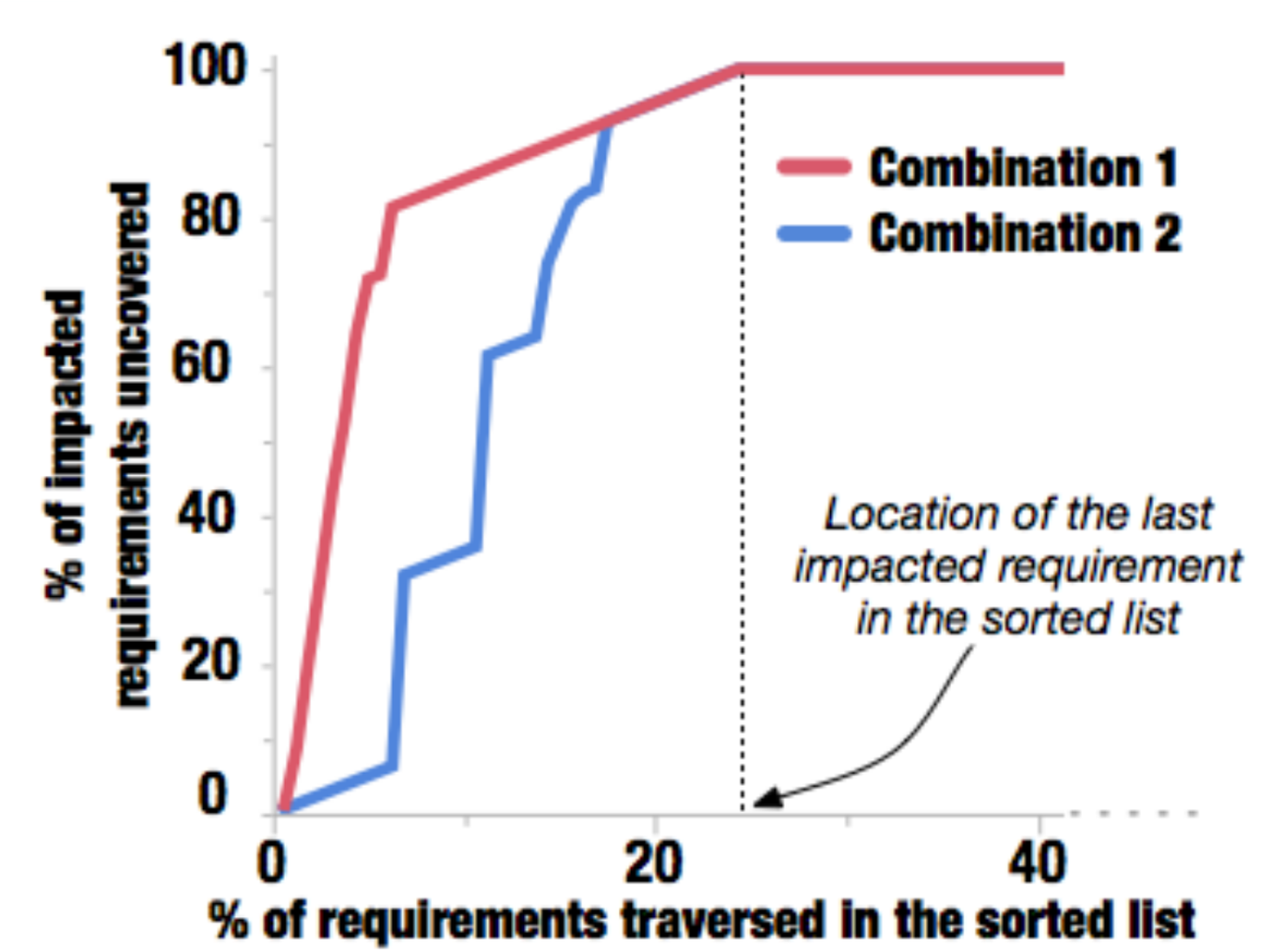
Rationale:

Avoid communication between mission operation controller and user help desk.

Propagation condition:

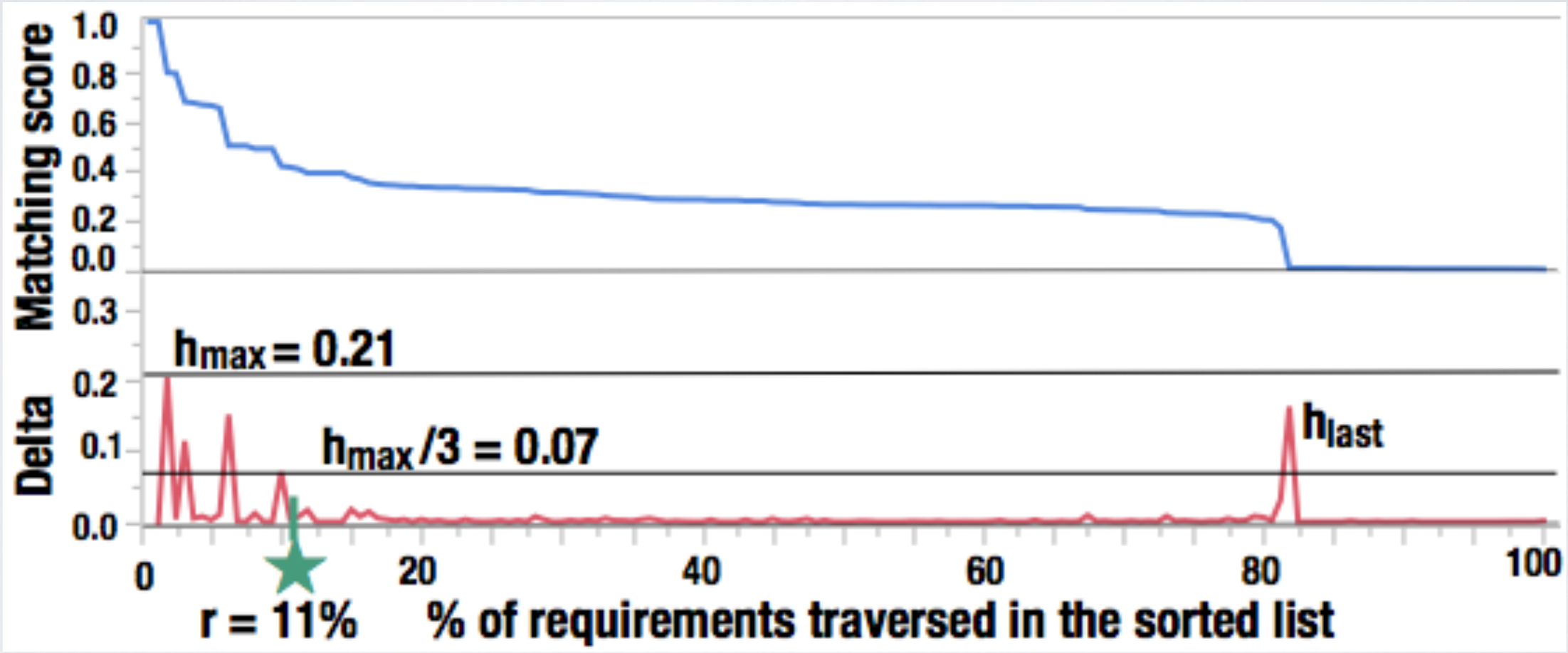
mission operation controller AND user help desk AND transmit

RQ1 - Which similarity measures are best suited to our approach?

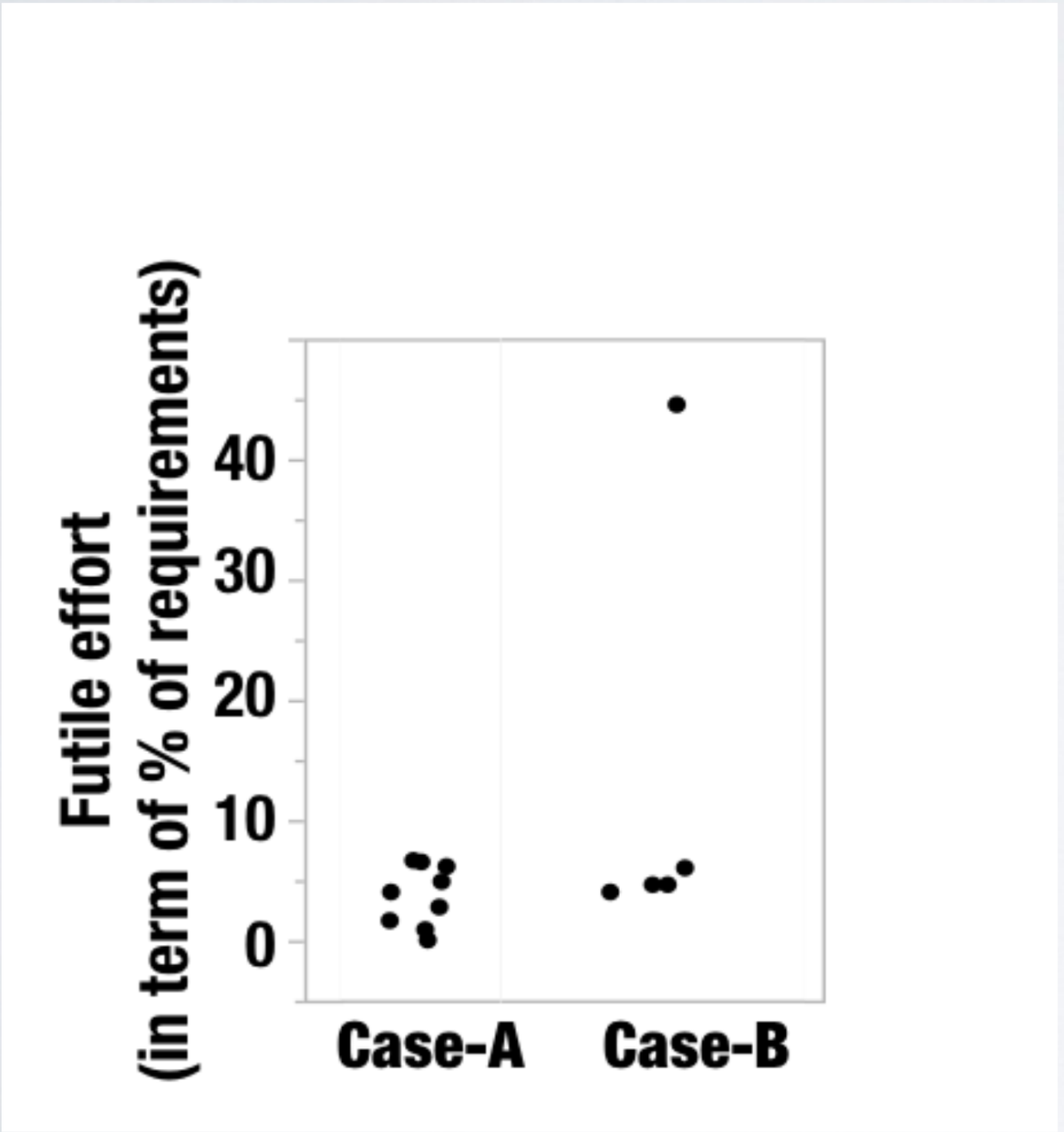


- Experimented with 10 syntactic, 9 semantic measures, and all their pairwise combinations (109 combinations)

RQ2 - How should analysts use the sorted requirements list produced by our approach?

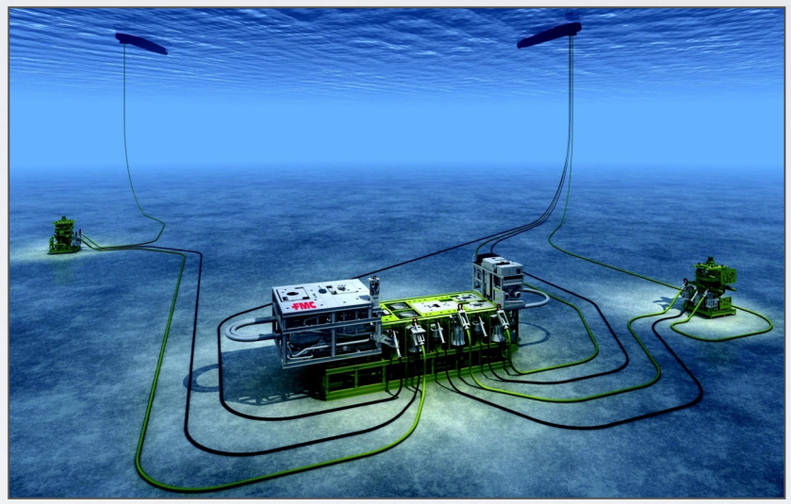


RQ3 - How effective is our approach?



- **Extra requirements traversed**
  - Case-A between 1%-7%
  - Case-B between 6%-8% except one case
- **Number of impacted requirements missed:**
  1 out of 106

Requirements-Design



KONGSBERG

FMC Technologies

[TOSEM 2014, IST 2012, FSE 2011, HASE 2011]

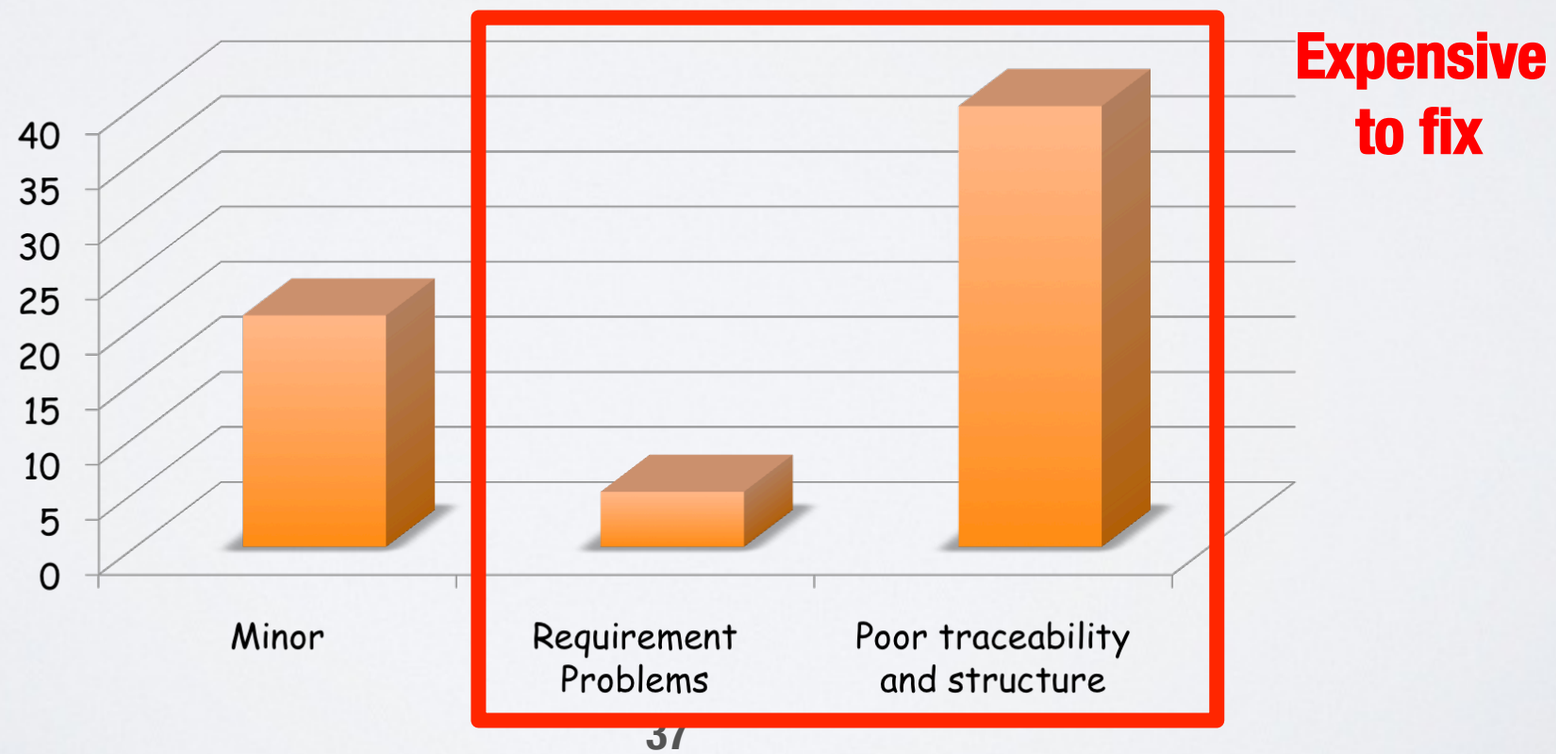
Requirements → Archi. & Design

Context

- **Context: Certification of safety-critical monitoring applications (fire and gas detection and emergency and process shutdown) in oil & gas industry**
- **Certification: Assessing and discussing software requirements, design/architecture and implementation documents**
- **Typically, many meetings taking place over 6 to 18 months**

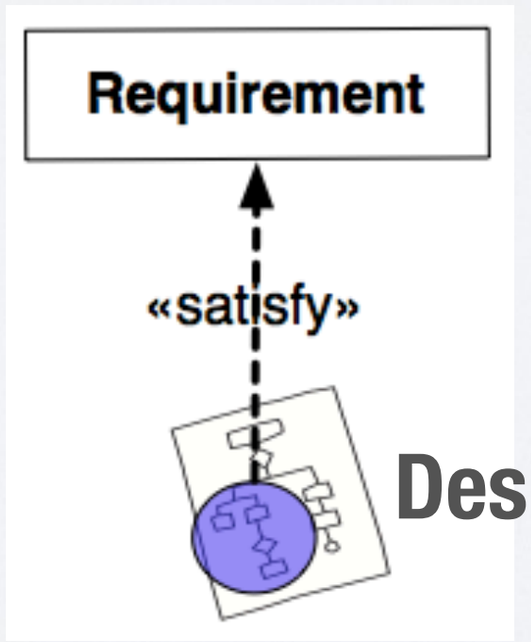
Observations

- **Analyzed 66 distinct certification issues:**
  - **Issues collected through observing certification meetings at different suppliers of maritime and energy systems**
- **Meetings focused on requirements, architecture, and design documents**



Research Objective

- Developing a **model-based traceability** methodology
- Generate a sound and yet minimal **design slice** for a given safety requirement, to support safety inspections
- Slices constructed based on traceability links established between safety requirements and design



Design Slice

Research Approach

Traceability Methodology

to relate safety requirements to design

Slicing Algorithm

to extract a design slice relevant to a given safety requirement

Model Driven Engineering (MDE) is the enabler

Modeling

- System Modeling Language (SysML)
  - A subset of UML extended with system engineering diagrams
  - A standard for system engineering
  - Preliminary support for requirement analysis and built-in traceability mechanism

Is SysML enough?

- Do we have proper guidelines for establishing traceability links between requirements and design?
  - SysML is only a notation and needs a methodology
- Are the built-in SysML traceability links capable of addressing certification traceability issues?
  - New traceability links: Source and assumptions of sys. safety reqs.
  - We specialized the semantics of existing ones: Refine, decompose, derive …
  - Explicit and implicit links

Research Approach

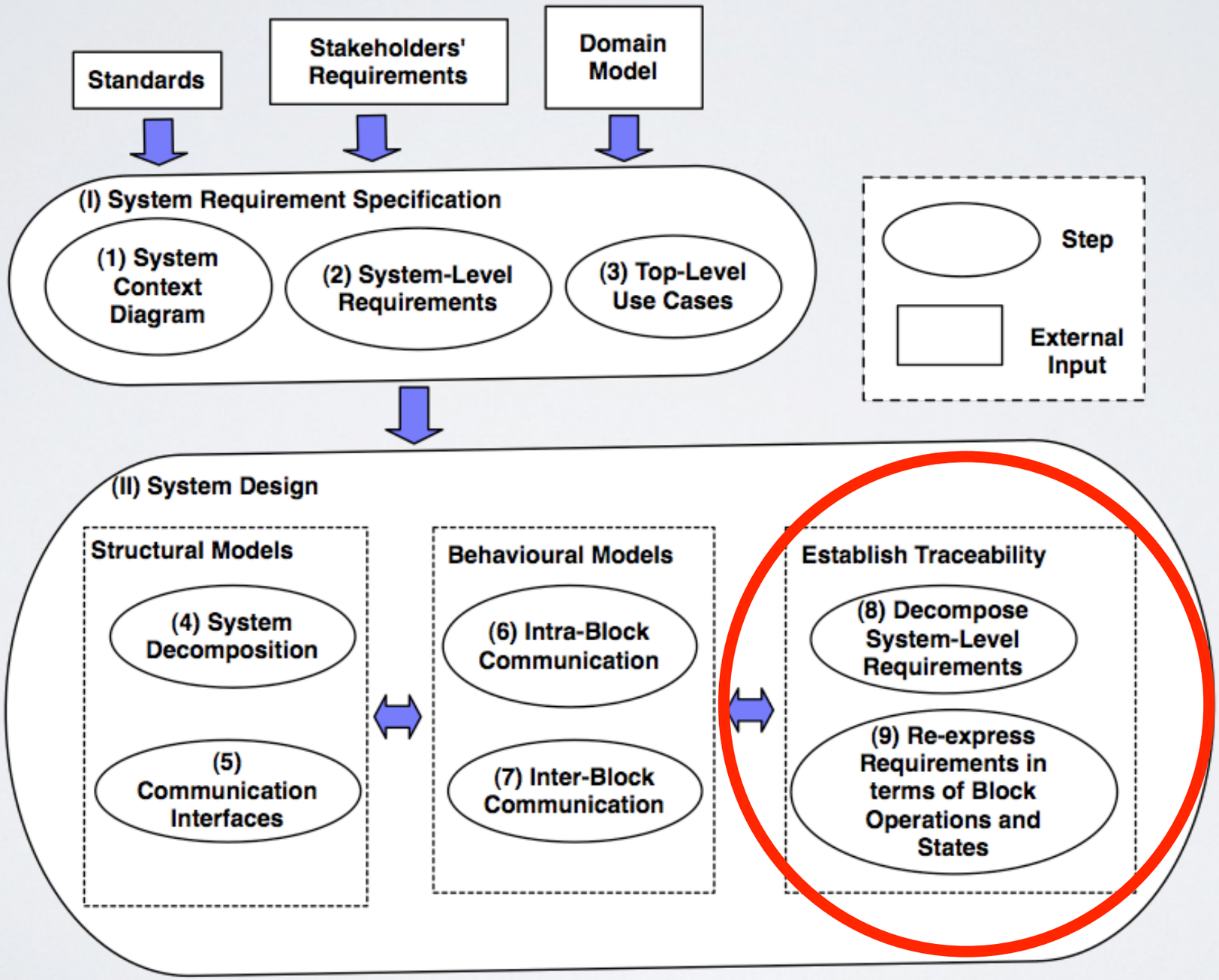
Traceability Methodology

to relate safety Requirements to design

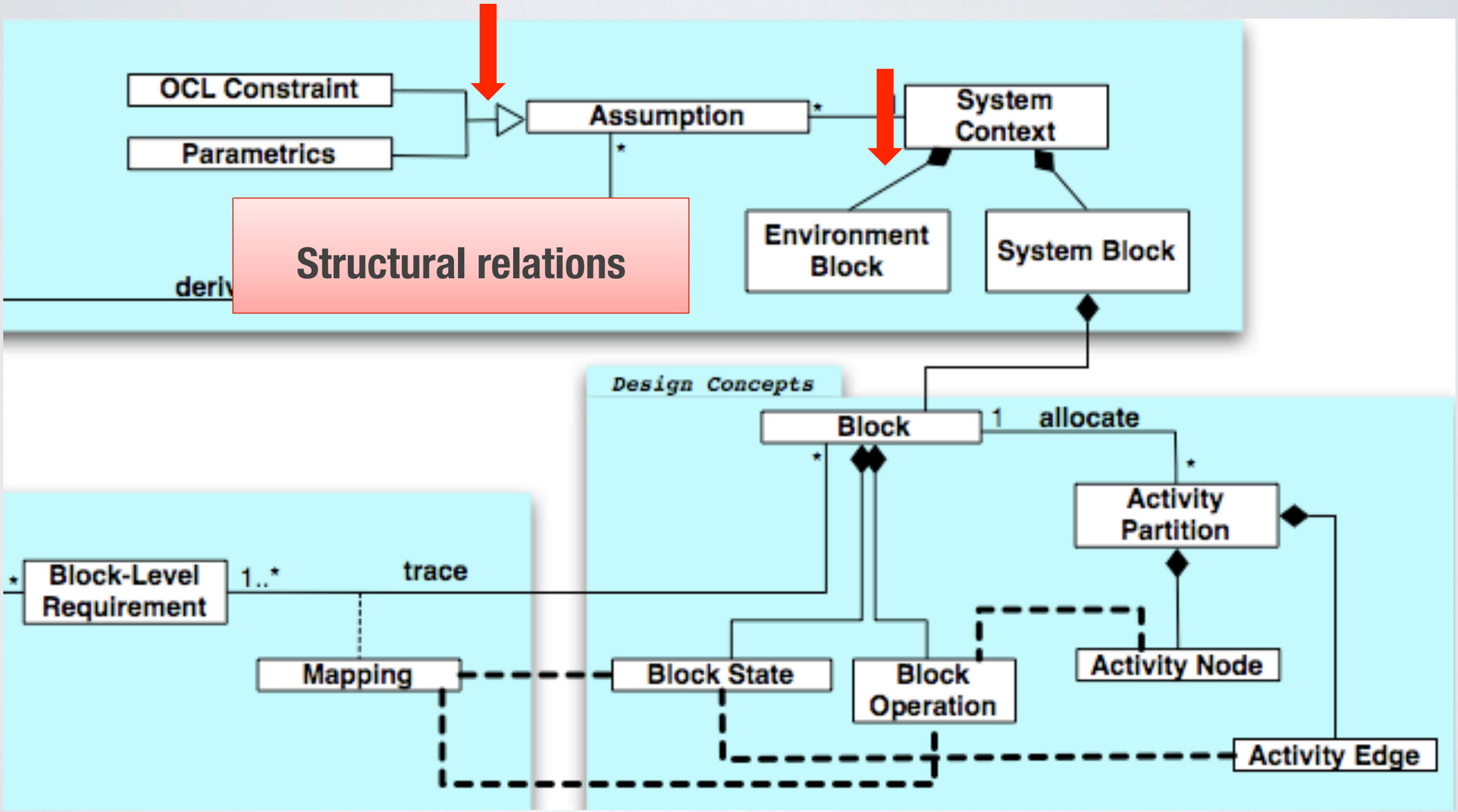
Slicing Algorithm

to extract a design slice relevant to a given safety requirement

Modeling Methodology



Traceability Information Model



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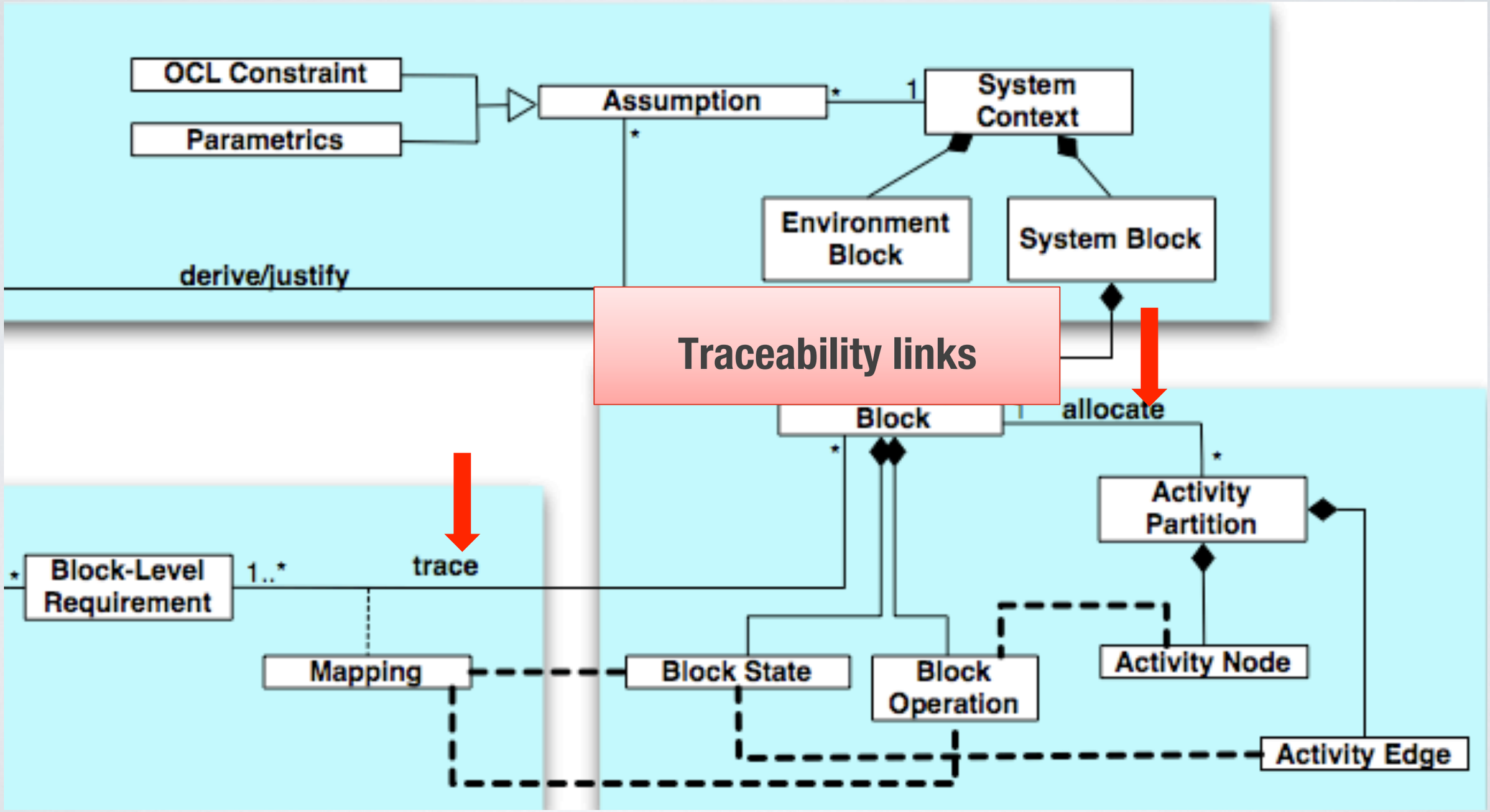

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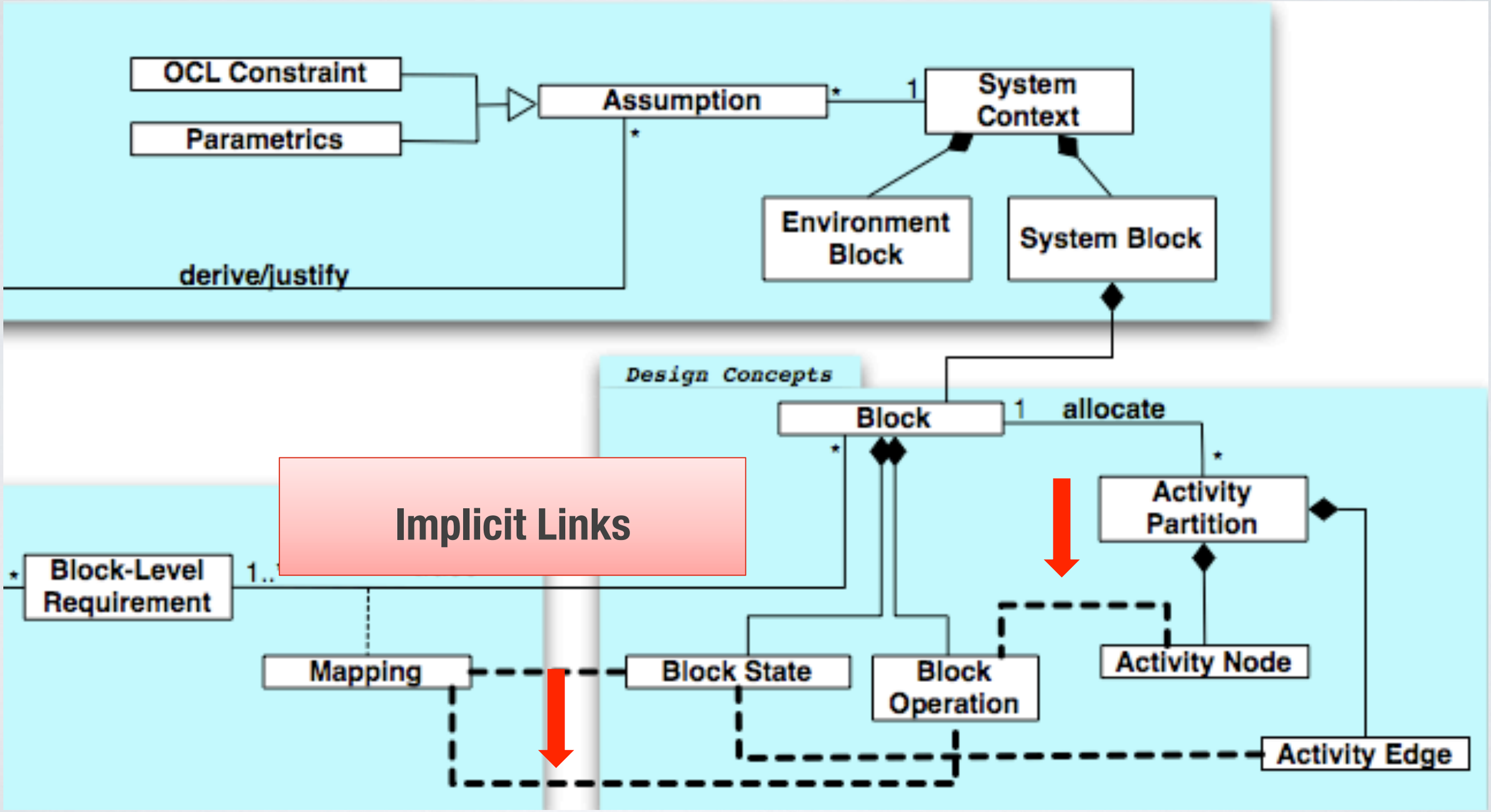
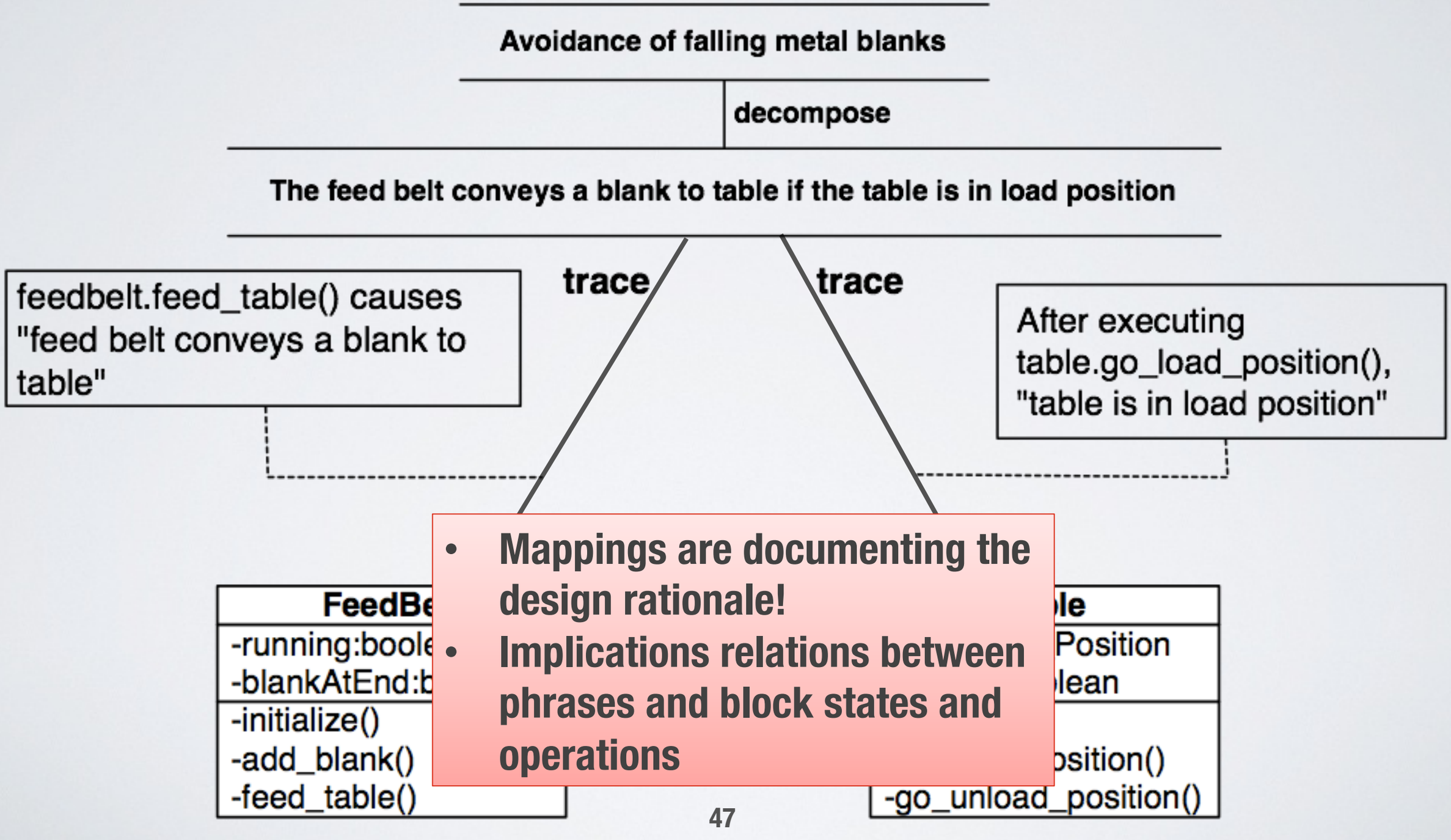
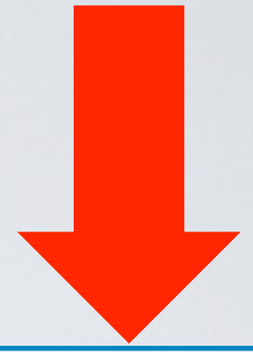


Requirement to Design Traceability



- Mappings are documenting the design rationale!
- Implications relations between phrases and block states and operations

Research Approach



Traceability Methodology

to relate safety Requirements to design

Slicing Algorithm

to extract a design slice relevant to a given safety requirement

Design Slicing

Avoidance of falling metal blanks

decompose

The feed belt conveys a blank to table if the table is in load position

feedbelt.feed_table() causes "feed belt conveys a blank to table"

trace

trace

After executing table.go_load_position(), "table is in load position"

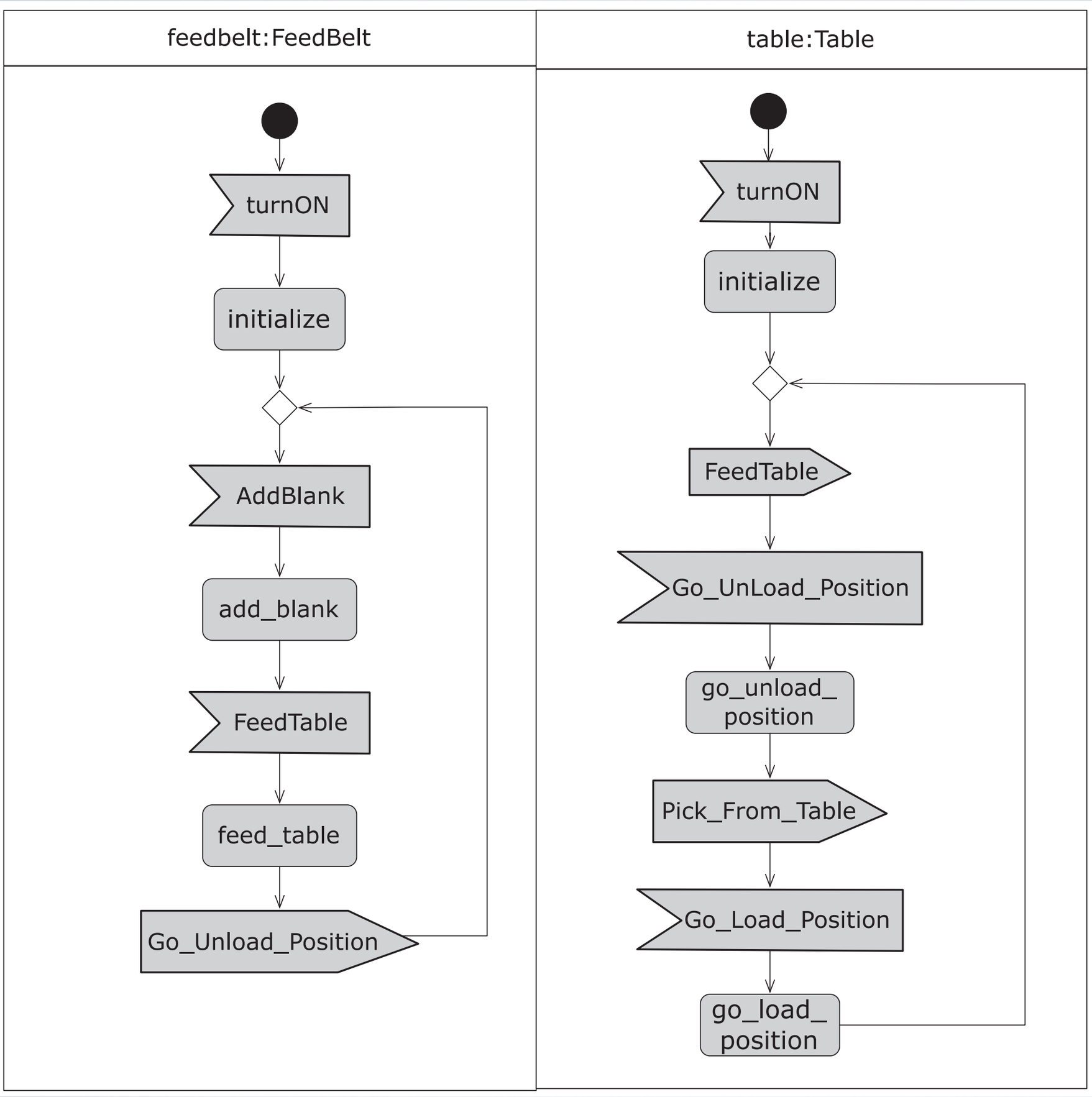
FeedBelt
-running:boolean -blankAtEnd:boolean
-initialize() -add_blank() -feed_table()

feedbelt ◀ **table**

1 **interact** **1**

Table
-pos:Table_Position -loaded:boolean
-initialize() -go_load_position() -go_unload_position()

Original Activity Diagram

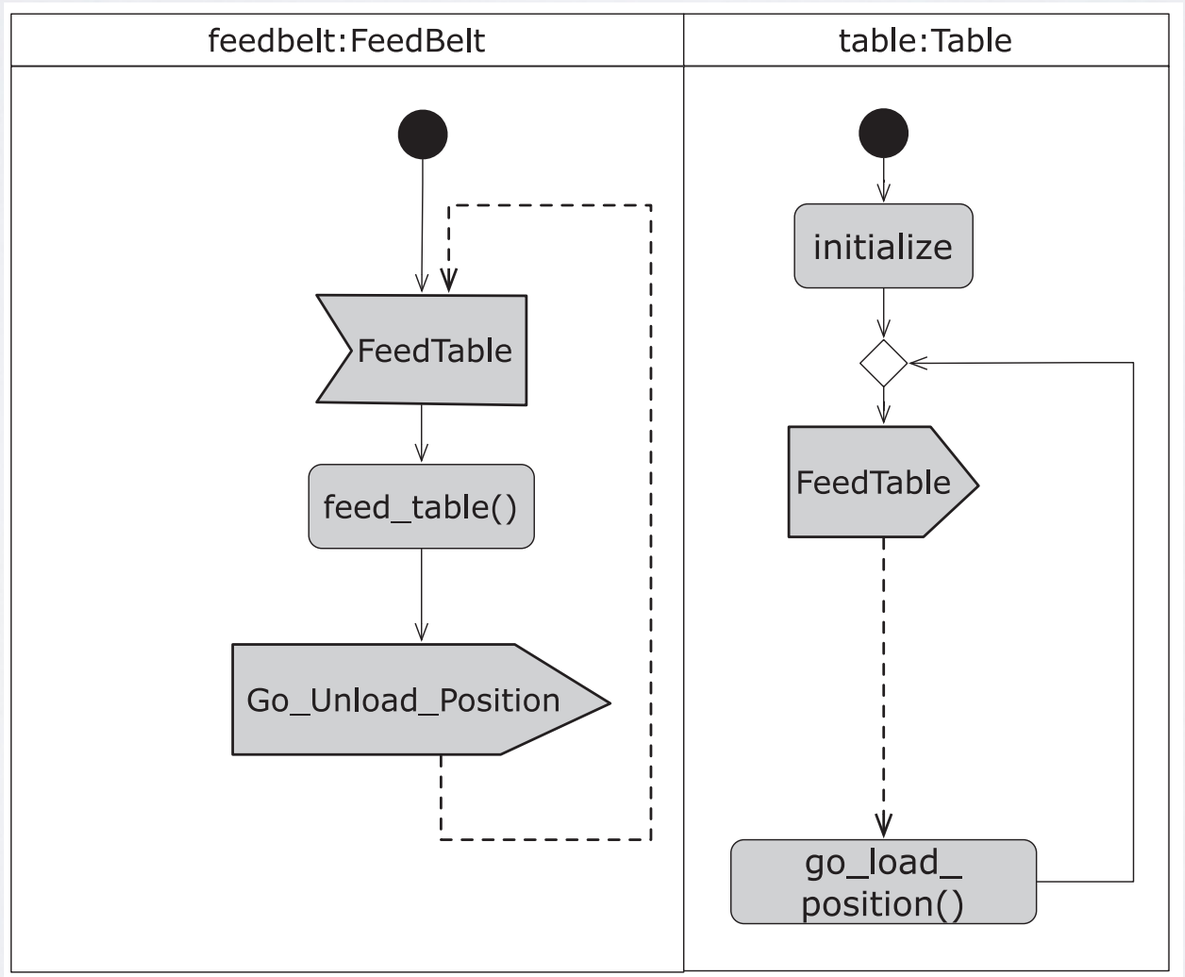


Slices

Avoidance of falling metal blanks

decompose

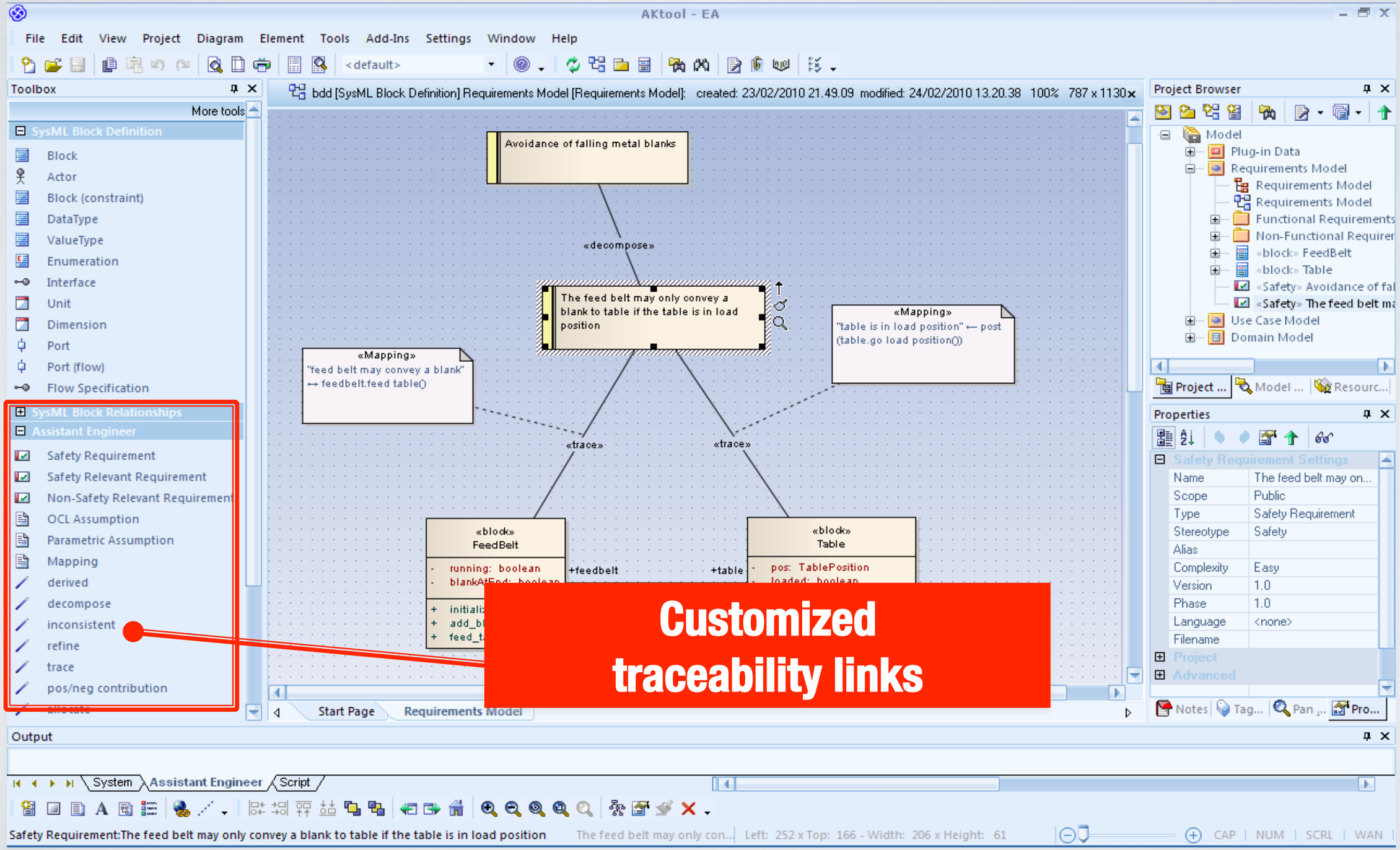
The feed belt conveys a blank to table if the table is in load position



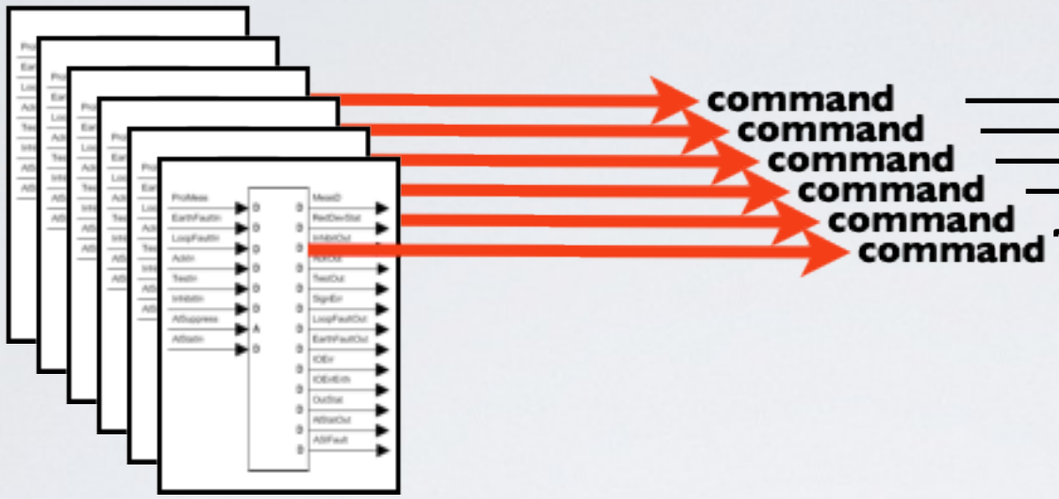
Slicing Algorithm

- If a requirement holds over a design slice, it should also hold over the original design (**soundness**)
  - Proven analytically (formal proof)
- If a requirement holds over the original design, then the design slice created for that requirement should conclusively satisfy that requirement (**completeness**)
  - Evaluated empirically (Case studies and experiments)

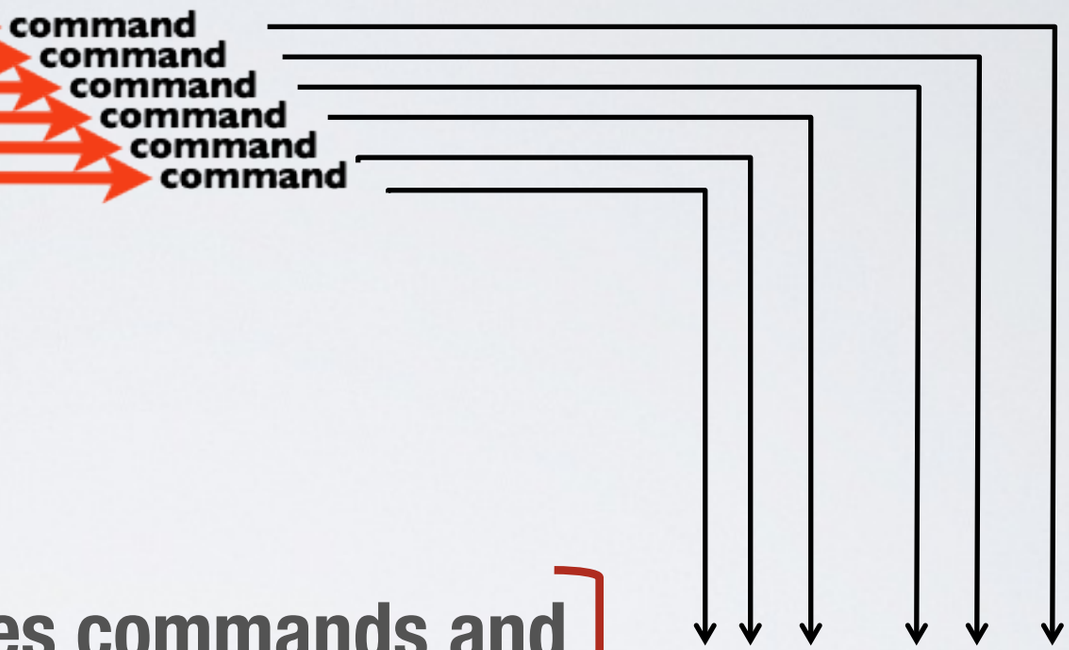
Tool Support



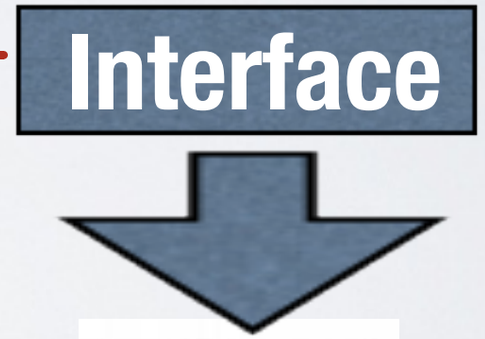
Case Study: SW/HW Interfaces



Control Modules



Communicates commands and data between control modules and hardware



Hardware

Goal: Practical guidelines to:

(1) Capture the concurrent design of interfaces

(2) Reduce the number and criticality of certification issues related to interfaces

Results

- Created design models with traceability to requirements
  - One context diagram (BDD), One architecture diagram (IBD), One detailed structure diagram (BDD), One activity decomposition diagram (BDD), One overall activity diagram, 19 detailed activity diagrams
  - Created 65 traceability links for 30 safety-relevant requirements
  - Modeling effort was approximately 40 person-hours
- Model Slicing
  - Extracted 34 block slices and 31 activity slices
  - Slicing reduced the number of block operations by 70% and the number of activity nodes by 50%

Controlled Experiment

- Question: Do safety slices help find design issues?
- Conducted in a laboratory setting with master students
- Overall design
  - Seeded faults into the design
    - Incorrect behavior and structure
  - Divided the subjects into two groups
    - One group gets the design without slices
    - One group gets the design plus the relevant slices

Experiment Results

- **Slices show strong benefits in terms of:**
- **Increasing the correctness of inspection decisions**
- **Decreasing the proportion of uncertain decisions**
- **Reducing the effort of inspections**

Recent Similar Experiment

- **Do developers benefit from requirements traceability when evolving and maintaining a software system?** Patrick Mäder, Alexander Egyed
- **Empirical Software Engineering (Springer), 2015**
- **Focus on program comprehension and maintenance**
- **Tasks with and without traceability**
- **Traceability led to 24% speed improvement and 50% better correctness**

Impact Analysis

- Automotive system (Delphi)
- Similar SysML modeling methodology
- Use models to support requirements change impact analysis

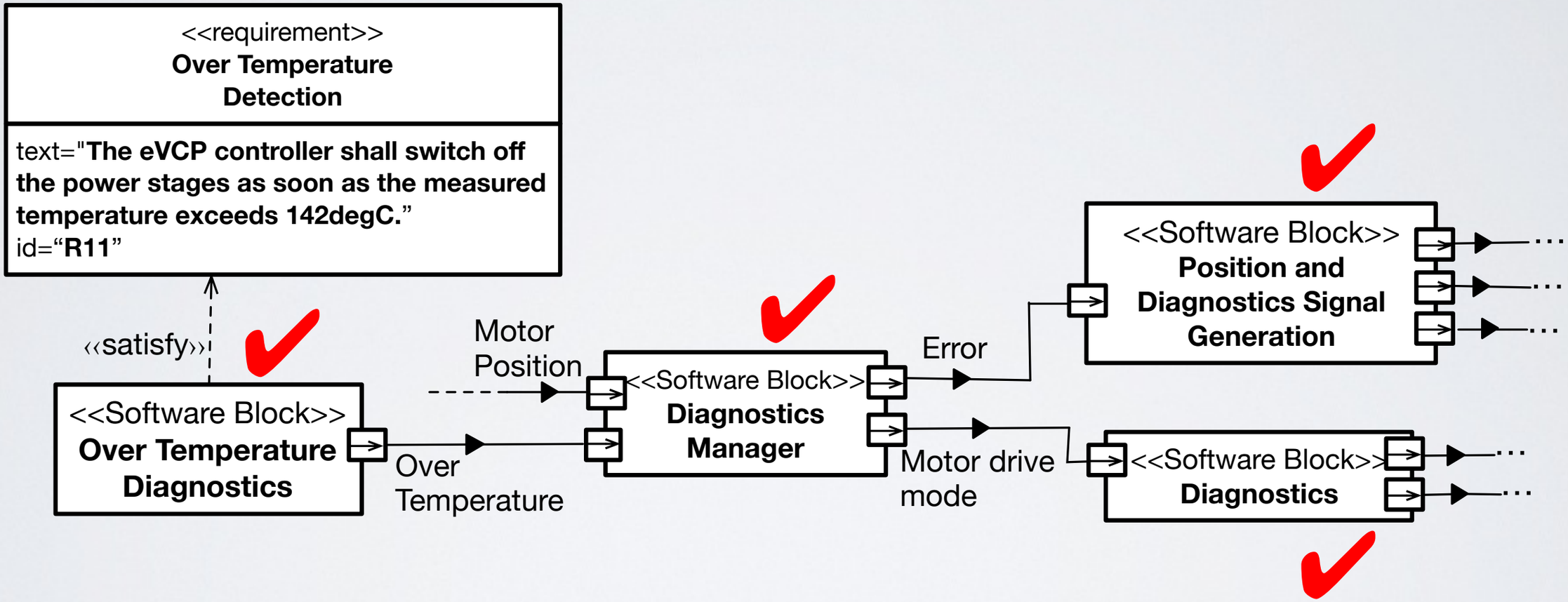
Our Objective

- Given a change in a requirement, our goal is to compute a set of (potentially) impacted elements that

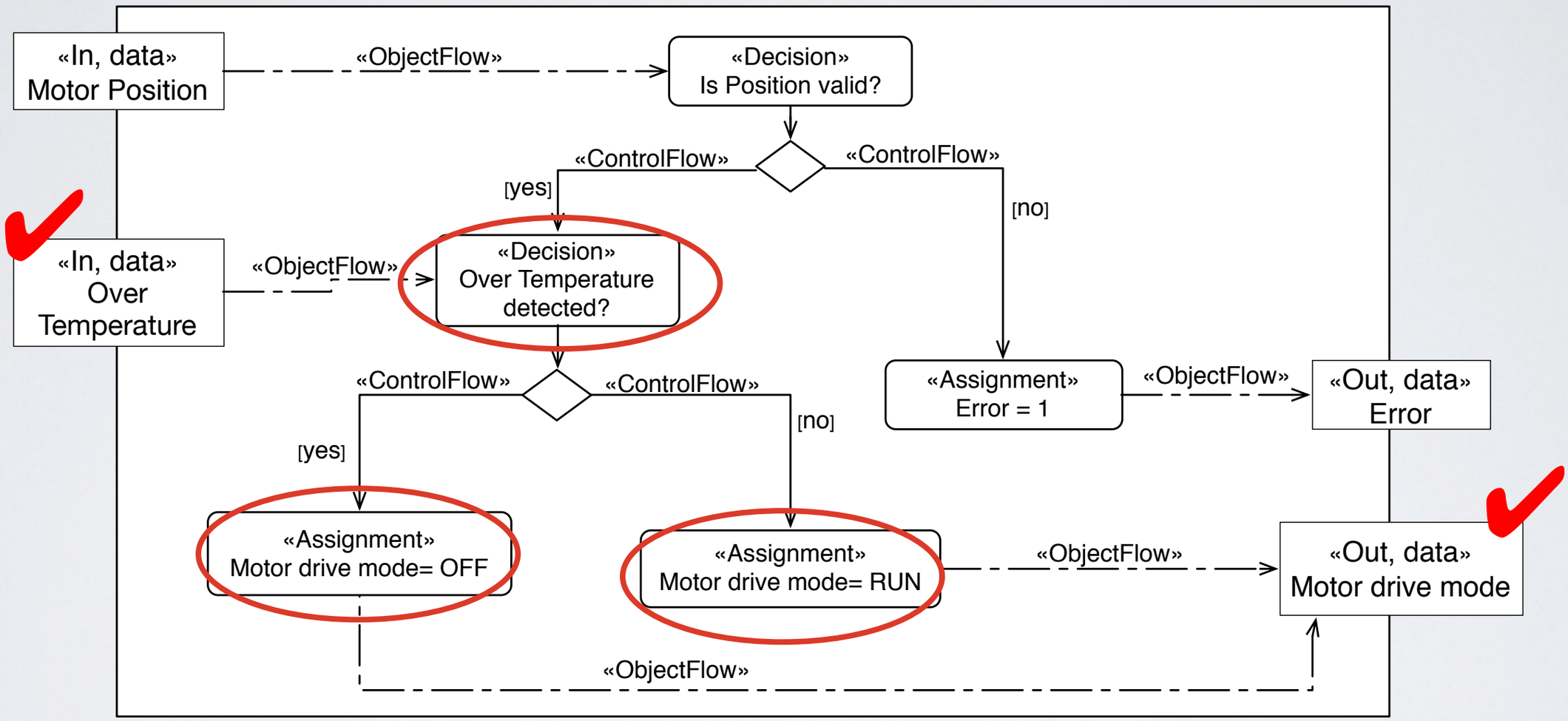
- (high recall) Includes all the actually impacted elements, and

- (high precision) Includes very few non-impacted elements (false positives)

Structural Analysis (Transitive Closure)

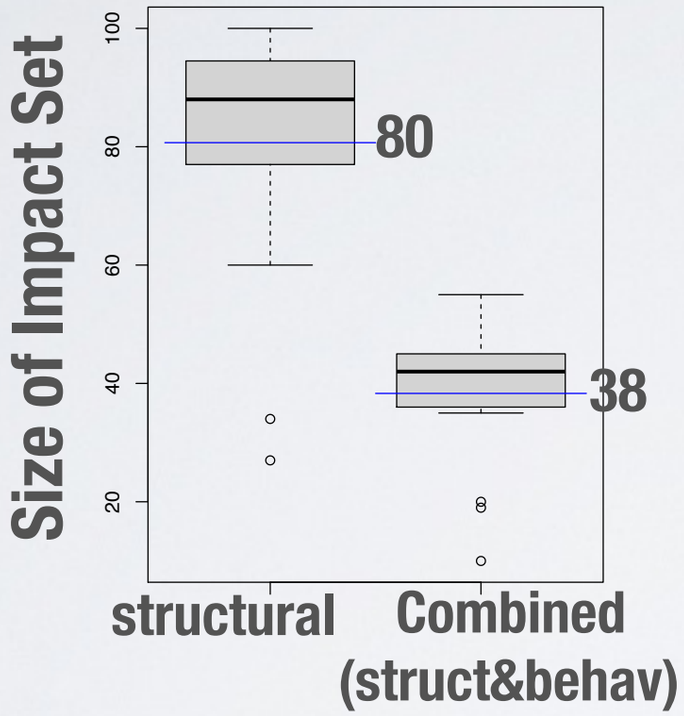


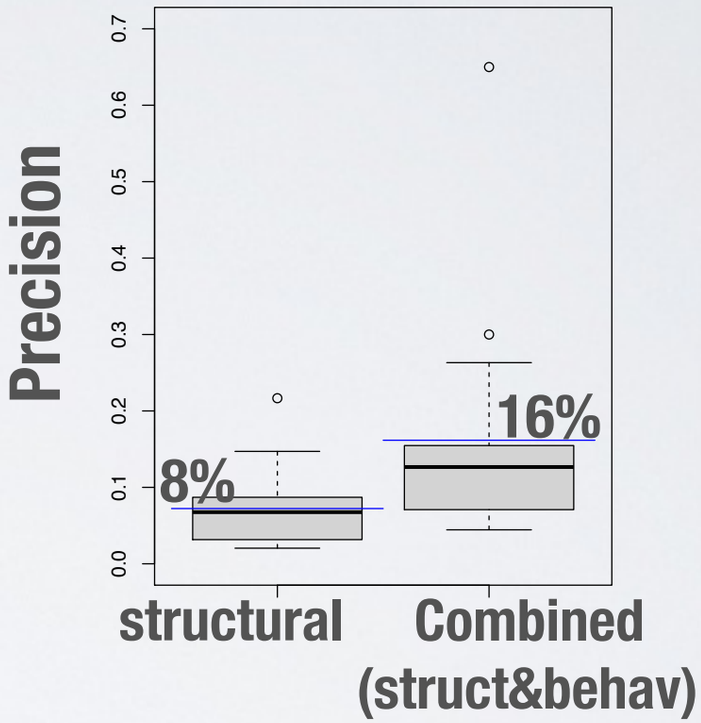
Behavioural Analysis (Forward Static Slicing)



Research Question (1)

- How much our Behavioral and Structural analysis can help in identifying actually impacted elements?





- The model size: 400
- Average impact set size after structural analysis: 80, and after combined structural and behavioral analysis: 38
- Recall for both structural and combined approaches: 100%

Analysis based on Natural Language Processing

- Two textual descriptions provided with a change request
  - A textual description of a change:

    E.g., Change to R12: Temperature range should be extended to -40/150 C from -20/120 C

  - A preliminary and early analysis of impact

E.g., impacts voltage divider (hardware) and lookup tables (software)

Our NLP-Based Analysis

- We identify noun phrases in change/impact descriptions (text chunking technique)
- We compare the similarity degree between these noun phrases and design element labels
  - Semantic NLP similarity measures
  - Syntactic NLP similarity measures
- We sort the design elements obtained after structural and behavioral analysis based on these similarity measures
- Engineers inspect the sorted lists to identify impacted elements

Research Question (2)

- **Which NLP Similarity Measures Perform Best?**

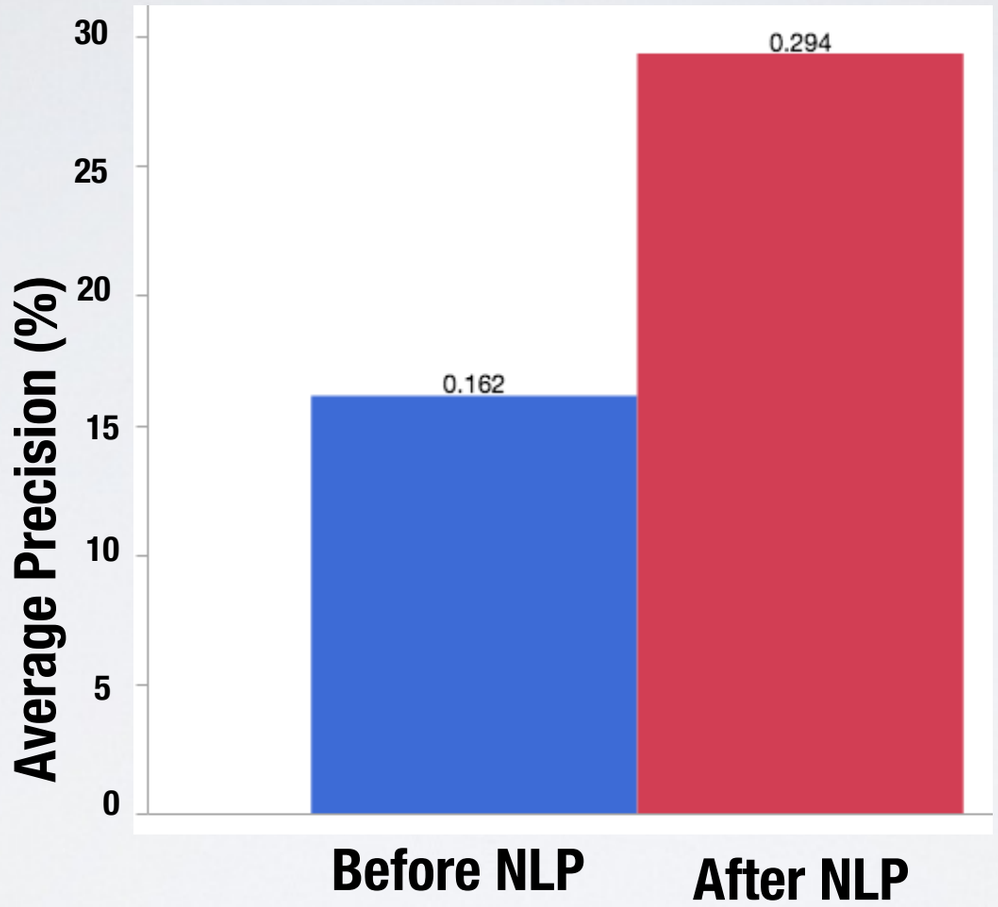
Syntactic Measures
Block Distance
Cosine Similarity
Dice's coefficient
Euclidean
Jaccard
SOFTTFIDF
Levenstein
Monge Elkan

Semantic Measures
HSO
LCH
JCN
LESK
LESK_TANIM
LIN
PATH
RES

Recommended Combination

Research Question (3)

- **How much improvement in Precision does our NLP technique bring about?**

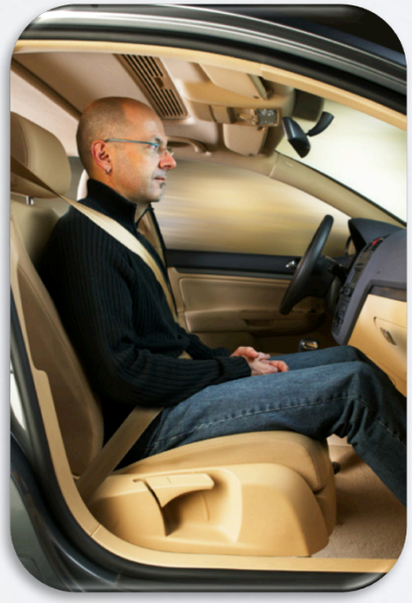


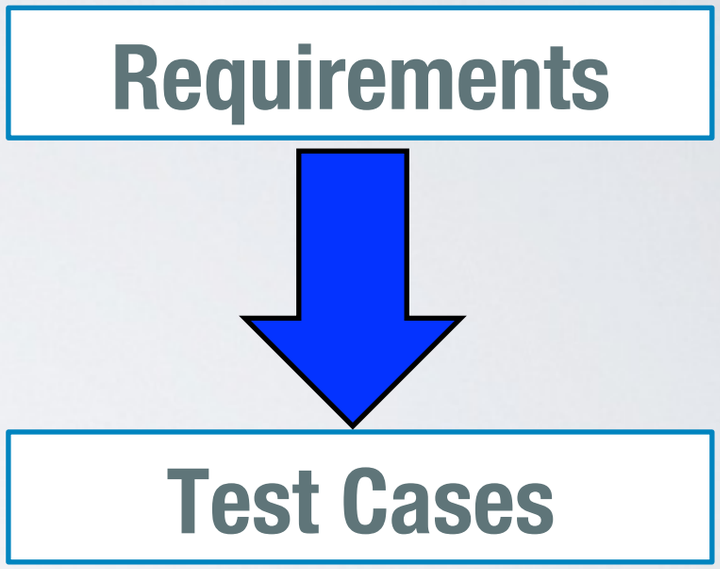
- **More than 13.2 % improvement in Precision after applying NLP**
- **Recall remains at 100%**
- **Engineers need to prune roughly two thirds of elements from the generated impact set**

Requirements-Test Cases

a sense for innovation IEE

BodySense





[ISSTA 2015]

Context

- Context: Automotive, sensor systems
- Traceability between system requirements and test cases
- Mandatory when software must undergo a certification process (e.g. ISO 26262)
- Customers require such compliance
- Use-case-centric development

Automated Test Generation

- Restricted use case specifications: Structure, templates, restricted natural language (RUCM)
- Domain modeling
- Constraints
- Automation combines Natural Language Processing and constraint solving
- Automated test generation comes with traceability between use case flows and system test cases

1 Elicit Use Cases

THE ACTOR SEND
THE ACTOR SEND
THE ACTOR SEND
THE SYSTEM VALI
T
T

RUCM Use Cases

2 Model the Domain

Domain Model

3 Evaluate Completeness

Missing Entities

4 Identify Constraints

TEMPERATURE IS LOW
STATUS IS VALID
ERRORS ARE ABSENT

List of Constraint descriptions

5 Specify Constraints

t > 0 and t < 50
Status <> null
Errors.size() = 0

OCL constraints

6 Generate Abstract Test Cases

Abstract Test Cases

Mapping Table

7 Generate Platform Specific Test Cases

Platform Test Cases

Case Study Results

Applicability

- Rewrote 6 use case specifications of BodySense
- 48 constraints to specify

Effectiveness

- Automatically generated test cases for 6 use cases
- Specific test strategy (Rationale)
- Approach covers more scenarios than manual testing: 100 versus 86
- Automated testing covers alternative flows not covered by manual testing

Discussion

- Modeling effort reasonable after initial training
- Main challenge is writing OCL constraints.
- Test generation time took about 12 min per test case, mostly due to constraint solving
- Engineers miss important test scenarios because
  - Path analysis across multiple use case specifications is difficult
  - Regular use case specifications are less precise that RUCM

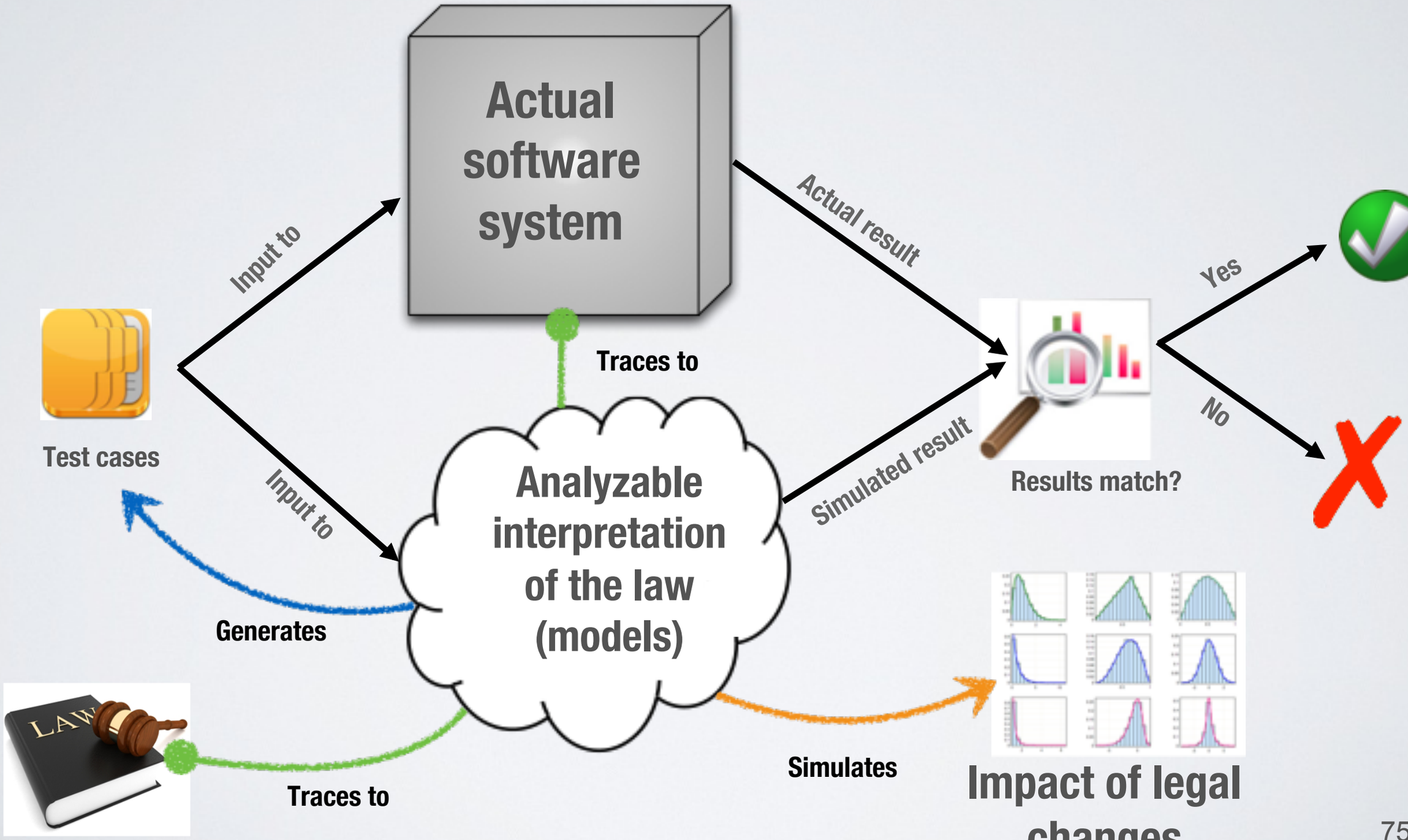
Regulations - Requirements

LE GOUVERNEMENT
DU GRAND-DUCHÉ DE LUXEMBOURG

- New tax system
- Customs and excise: complex European laws
- Systems need to be compliant with the law and remain so over time

[RE 2014, MODELS 2014]

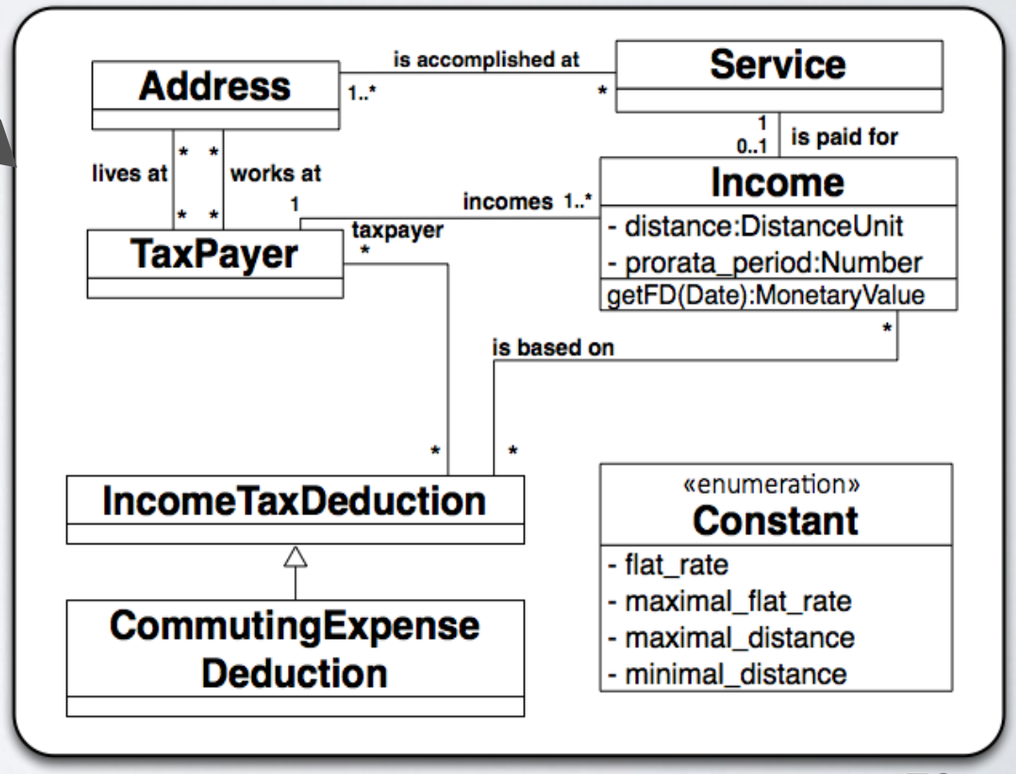
Solution Overview



Example

Art. 105bis […]**The commuting expenses deduction (FD)** is defined as a function over the distance between the principal town of the municipality on whose territory the taxpayer's home is located and the place of taxpayer's work. The **distance** is measured in units of distance expressing the kilometric distance between [principal] towns. A ministerial regulation provides these distances.

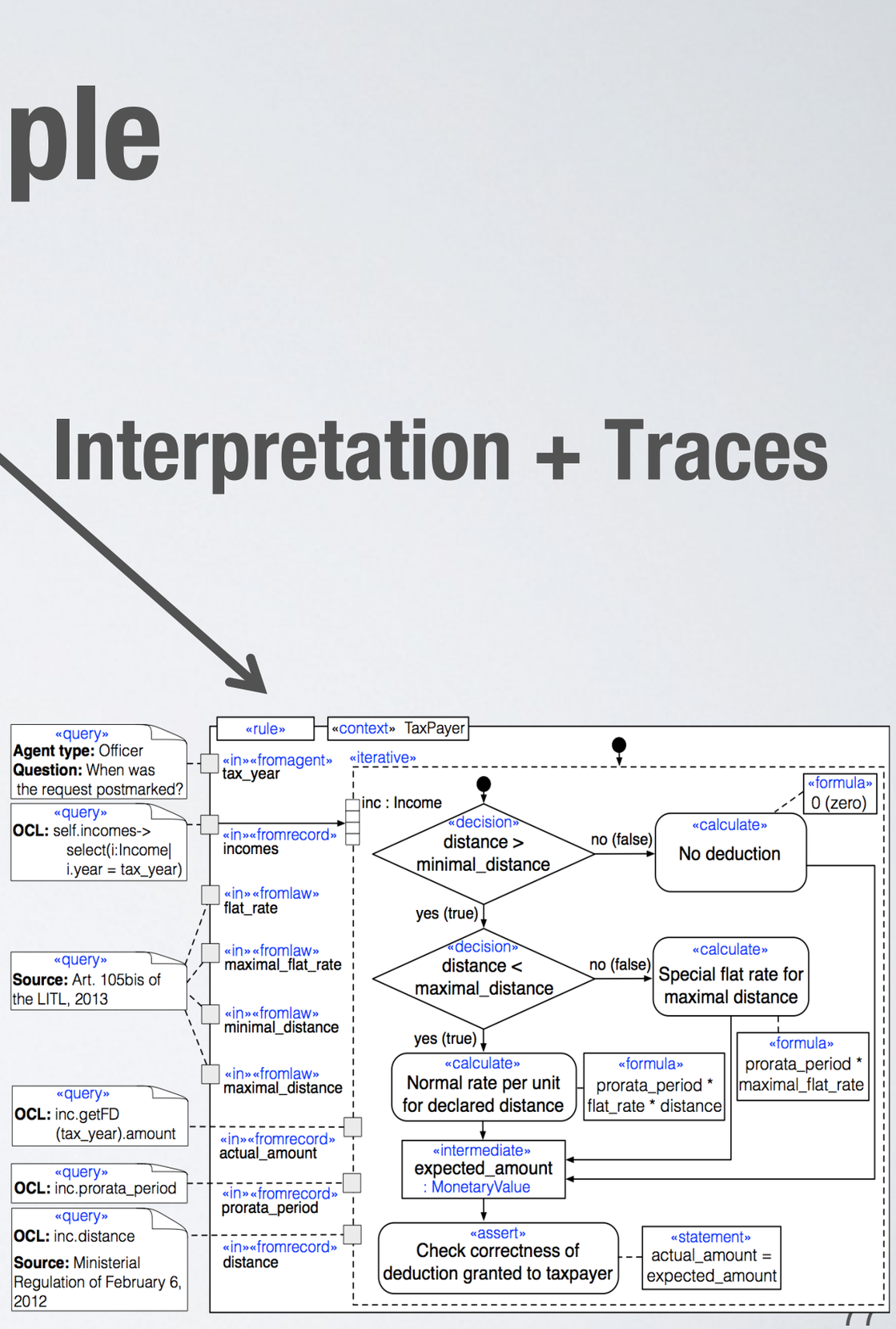
Interpretation + Traces



Example

The amount of the deduction is calculated as follows:
If the distance exceeds **4** units but is less than **30 units**, the deduction is **€ 99** per unit of distance.
The first **4 units** does not trigger **any deduction** and the deduction for a distance **exceeding 30** units is limited to **€ 2,574**.

Interpretation + Traces



Discussion

- We addressed the gap between legal experts and IT specialists
- Models understandable by both legal experts and IT specialists
- Modeling effort was considered reasonable given the life span of such eGovernment systems
- Traceability to the law was considered a significant asset given frequent and complex changes in the law

Conclusions

Conclusions

- From an economic standpoint,
  - the accuracy of trace recovery techniques cannot be interpreted out of context
  - what traceability information to capture is a trade-off
  - benefits depend on context
- More human studies are required to assess cost-benefits
- Design of such studies is not easy: baseline of comparison, comparable tasks, training, comparable skills …

Conclusions

- Change impact analysis among requirements was surprisingly accurate
- Change rationale needed to be captured
- But this is expected to depend on requirements writing practice, e.g., precision and consistency
- Accurate inter-requirements traces may require capturing tacit dependencies between domain concepts, e.g., domain model
- What type of domain model do we need? Ontologies?
- Can accuracy be improved through the use of NL templates?

Conclusions

- Requirements-design traces require a precise design methodology, including practical mechanisms to capture design rationale and link it to requirements
- Documenting design rationale cannot be automated, but can be facilitated
- Questions, in each new context:
  - What is the right Modeling methodology?
  - What is the right trace granularity?
  - What information do traces need to carry?
- Change impact analysis: Models are expensive, tradeoff between modeling requirements and accuracy, combining model analysis and NLP can be effective

Rationale Matters!

Traceability is an economic decision

Context Matters!

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- [IST 2012] S. Nejati et al., A SysML-Based Approach to Traceability Management and Design Slicing in Support of Safety Certification: Framework, Tool Support, and Case Studies

- [HASE 2011] M. Sabetzadeh et al., Using SysML for Modeling of Safety--Critical Software--Hardware Interfaces: Guidelines and Industry Experience

- [FSE 2011] D. Falessi et al., SafeSlice: A Model Slicing and Design Safety Inspection Tool for SysML

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- [MODELS 2014] G. Soltana et al., UML for Modeling Procedural Legal Rule

- [RE 2014] M. Adedjouma et al., Automated Detection and Resolution of Legal Cross References

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- **[IJSEKE 2012]** R. Torkar et al., Requirements Traceability State-of-the-art: A systematic Review and Industry Case Study

- **[FOSE 2014]** J. Cleland-Huang et al., Software Traceability: Trends and Future Directions

Traceability Beyond Source Code: An Elusive Target?

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